(12) FG.

AD A032198

SPD-525-01

TRIAL RESULTS OF SHIP MOTIONS AND THEIR INFLUENCE ON AIRCRAFT OPERATIONS FOR ISCS GUAM

DAVID W. TAYLOR NAVAL SHIP RESEARCH AND DEVELOPMENT CENTER

Bethesda, Md. 20084

TRIAL RESULTS OF SHIP MOTIONS AND THEIR INFLUENCE ON AIRCRAFT OPERATIONS FOR ISCS GUAM

by

A. Erich Baitis

and

Dennis A. Woolaver

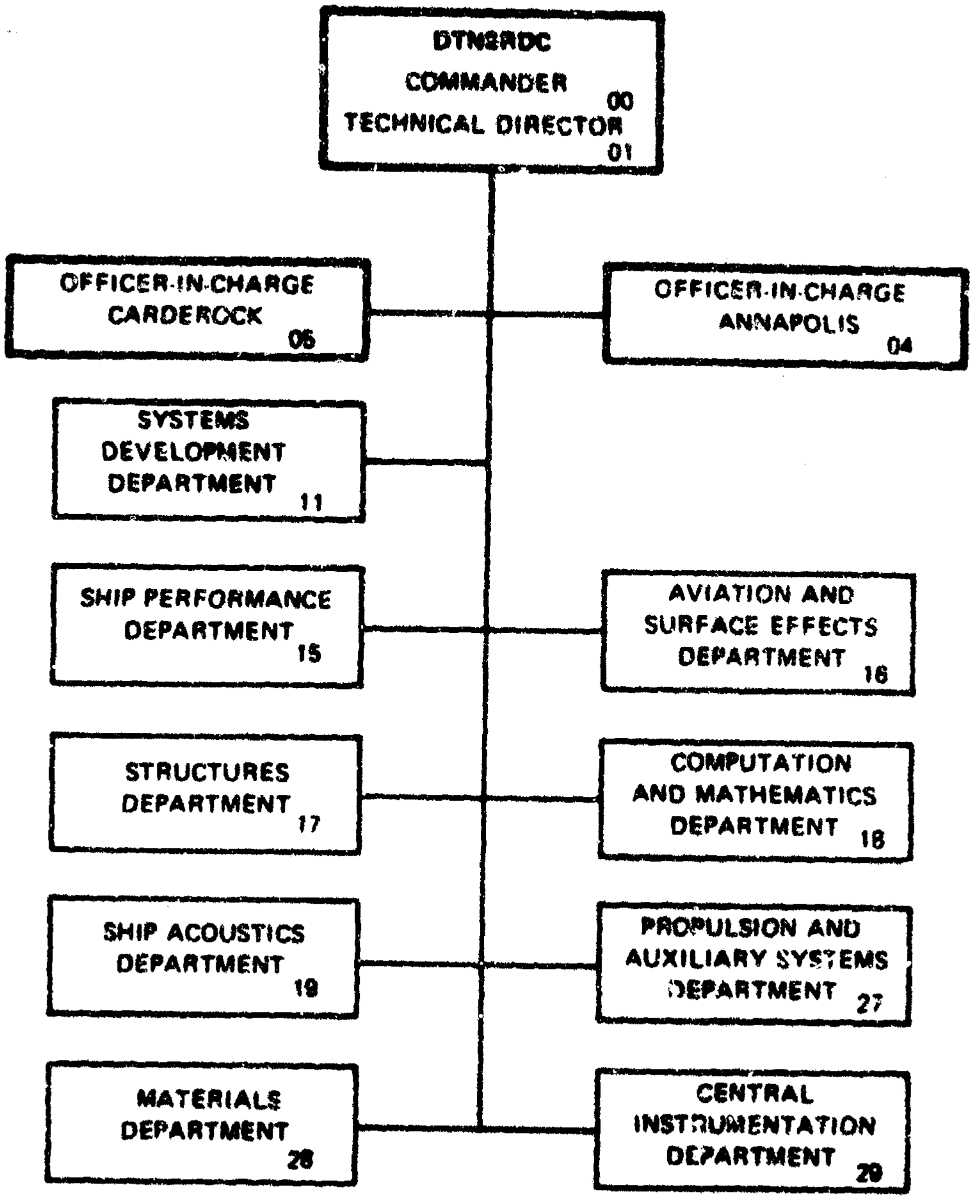
APPROVED FOR PUBLIC RELEASE: DISTRIBUTION UNLIMITED

SHIP PERFORMANCE DEPARTMENT

December 1975

SPD-525-01

MAJOR DTNSRDC ORGANIZATIONAL COMPONENTS



UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER 14 SPD-525-01	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) 6 TRIAL RESULTS OF SHIP MOTIONS AND THEIR INFLUENCE ON AIRCRAFT OPERATIONS FOR ISCS GUAM.		5. TYPE OF REPORT & PERIOD COVERED 9 Final rept. 6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) 10 A. Erich/Baitis [redacted] Dennis A./Woolaver		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Ship Performance Department David W. Taylor Naval Ship R&D Center Bethesda, Maryland 20084		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS Work Unit Number 1-1568-811
11. CONTROLLING OFFICE NAME AND ADDRESS Naval Sea Systems Command (PMS 397) Washington, D.C. 20362		12. REPORT DATE 11 Dec[redacted]75 (Reissue) 13. NUMBER OF PAGES 110 12 113p.
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office) Naval Ship Engineering Command (Code 6136) Prince Georges Center Hyattsville, Maryland 20782		15. SECURITY CLASS. (of this report) Unclassified 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

APPROVED FOR PUBLIC RELEASE: DISTRIBUTION UNLIMITED

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Interim Sea Control Ship, VSTO Aircraft, AV8A "Harrier", Ship motions, Aircraft operations at sea, Aircraft cancellations and delays, Motion lulls, Motion prediction, Limiting ship motions, Motions degrading aircraft maintenance, Roll stabilization

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The Naval Ship Research and Development Center made ship motion/aircraft event correlation measurements on board the Interim Sea Control Ship (USS GUAM, LPH-9) during various deployments in 1971, 1972, and 1973. The primary objectives of these measurements were to collect and define ship motions which limit aircraft takeoffs and recoveries and to evaluate the effectiveness of GUAM's anti-roll tank.

(continued)

DD FORM 1473, 1 JAN 73 EDITION OF 1 NOV 65 IS OBSOLETE

S/N 0102-014-6601

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

389 694

While emphasis is placed on the takeoff and recovery states as observed for the British VSTOL Harrier, or AV8, significant comments, based on the analysis of observed and recorded data, are presented for other stages in the aircraft operational cycle. Several analysis methods are employed to define aircraft operation limiting ship motions, the most critical ship motion or combination thereof that interfere with aircraft operations, and the operational procedures relating to ship motions developed during the Interim Sea Control Ship deployments.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

NOMENCLATURE

SCS	Sea Control Ship
ISCS	Interim Sea Control Ship
LPH	USN Helicopter carrier
A/C	Aircraft
AV8, AV8A	British VSTOL aircraft, Harrier
H-3	USN Helicopter, ASW
LAMPS	USN Helicopter, Light Airborne Multi-Purpose System
ASW	Anti-submarine warfare
VSTOL	Vertical short takeoff and landing aircraft
STO	Short rolling takeoff
VT	Vertical takeoff
VL	Vertical landing
TSL	Translated starboard landing
PRI-FLY	Primary flight control tower, GUAM
LSO	Landing signal officer
LSE	Landing signal enlisted
NATOP	USN Tactical Operations manual
WOD	Wind over deck
WT	Weight
OPS	Operations, various types
OPTEVFOR	Operational Test and Evaluation Force
DTNSRDC	Formerly NSRDC, Naval Ship Research and Development Center
NAEC	Naval Air Engineering Center
NAVSEC	Naval Ship Engineering Center
NAVSHIP	Naval Ship Systems Command, now NAVSEA
NAVSEA	Naval Sea Systems Command

ABSTRACT

The Naval Ship Research and Development Center made ship motion/aircraft event correlation measurements on board the Interim Sea Control Ship (USS GUAM LPH-9) during various deployments in 1971, 1972, and 1973. The primary objectives of these measurements were to collect and define ship motions which limit aircraft takeoffs and recoveries and to evaluate the effectiveness of GUAM's anti-roll tank.

While emphasis is placed on the takeoff and recovery stages as observed for the British VSTOL Harrier, or AV8, significant comments, based on the analysis of observed and recorded data, are presented for other stages in the aircraft operational cycle. Several analysis methods are employed to define aircraft operation limiting ship motions, the most critical ship motion or combination thereof that interfere with aircraft operations, and the operational procedures relating to ship motions developed during the Interim Sea Control Ship deployments.

ADMINISTRATIVE INFORMATION

This work was carried out by the Naval Ship Research and Development Center under Job Order Number 1-1568-811 in response to the Naval Ship Engineering Center's Work Requests WR-2-5501, WR-2-5365, WR-3-5146, WR-3-5234, WR-3-5323 and WR-4-5138.

INTRODUCTION

The Naval Ship Research and Development Center made ship motion/aircraft event correlation measurements on board the USS GUAM for 18 months ending in May 1973. The ship motion related results of these extended ship/aircraft operational trials were published informally in a limited distribution NSRDC Ship Performance Department Evaluation Report in February 1974.

Since the various data collected during these many deployments are of general interest to future naval VSTOL aircraft operations from ships, the report is being reissued as a David W. Taylor NSRDC Ship Performance Department Research and Development Report with unlimited distribution.

The main objectives of the NSRDC measurements and observations during the various deployments of the USS GUAM as the Interim Sea Control Ship were

1. collect ship motions which limit aircraft operations
2. evaluate the GUAM's anti-roll tank

The collection of ship motion data which limit aircraft operations was regarded as the most important measurement objective. The results of the GUAM's anti-roll tank evaluation are given in Appendix A.

Although the Interim Sea Control Ship (ISCS) employed both helicopters and the new British VSTOL aircraft AV8's or Harriers, motion limits on Harrier operations were emphasized in the collection and analysis of the data. In fact, no analysis of the helicopter data has been made at this time. In addition, even though ship motions limit aircraft

operations at all stages in the aircraft operational cycle on the ship, only the takeoff and recovery portions of this cycle were emphasized.

It should be pointed out that the NSRDC crew rode the ship as observers and, as such, had no direct input into the ship maneuvers when ship motions that apparently limited aircraft operations were encountered. Indirectly, however, the NSRDC measurements were utilized by the operators when these limiting ship motions occurred. At such times the ship would request motion values for "that last large roll and pitch." This value was clearly recognized by both the operators and the NSRDC representatives. It is to be noted that these values of ship motions were transmitted as double amplitudes i.e., peak-to-trough values. This convention of specifying double amplitudes of ship responses as well as the use of the Harrier aircraft based motion criterion of pitch plus roll has been maintained in the data analysis. Thus the analysis is intentionally related back to the procedures and aircraft/equipment capabilities noted during the GUAM at-sea periods.

MEASUREMENT AND ANALYSIS PROCEDURES

MEASURED AND OBSERVED DATA

The types of measured and observed data recorded on the GUAM are illustrated along with the location of the observers and transducers in Figure 1. During some of the GUAM deployments a staff member from NAEC supplemented the NSRDC trial group. During such trials NAEC collected data designated by • in Figure 1. Three basic types of data were collected. These are

1. ship motion measurements

2. aircraft (A/C) operational procedures

3. audio visual data

The electronically measured data were collected in a centralized instrumentation room located near the bow. Aircraft operational procedural and audio-visual data was collected by the NSRDC engineers stationed in the GUAM's primary flight control tower, i.e., PRIFLY. Every Harrier aircraft event was thus observed and recorded by NSRDC engineers during the GUAM deployments.

Bow acceleration(1) and the relative motion(2) between the bow of the GUAM and the water surface at the bow were measured to determine sea state, and to determine the height above the water of the aircraft the instant it took off from the ship.

Unfortunately, difficulties with the recorded wave height data precluded an efficient analysis of this data. To save time and effort therefore, the observed wave height obtained from the GUAM's meteorology department were used throughout this report as the "wave height and swell." It should be noted in this connection that the observed wave height (sea) and swell were combined to obtain the total wave height H, by

$$H^2_{total} = H^2_{swell} + H^2_{sea} \quad . \tag{1.1}$$

The total wave height was categorized into sea states in accordance with Table 1.

Pitch, roll, and the three components of acceleration near the AV8 touchdown point(5) were measured to define ship responses to the measured/

observed sea conditions. These measurements were made on the centerline, one level below the flight deck, 36 feet forward of the aft perpendicular of the ship. This longitudinal location of the measurement point corresponds to the most frequent location of Harrier touchdowns during landings and starts during the short takeoffs. Ship course[3], speed[4] and event time[6] completed the electronic measurements made to establish ship motions which limit aircraft operations. Additionally, it should be noted that the output of the ship's own speed transducer was recorded as ship speed. Analysis of the recorded ship speed indicated that this recording was not functioning properly during all of the deployments. The reported ship speed therefore was obtained either from the ship's transducer when this was working or from the algebraic summation of the speed and direction of the prevailing surface wind at the time of the event and the speed and direction of the wind over deck at the time of the event. Since the surface wind speed was not constant but subject to gusts, the wind over deck speed was averaged over several events where such events occurred shortly before or after the event under consideration. The resultant ship speeds are considered to be representative of the actual speed at the time of the event. Surface wind speed and direction was obtained from weather observations taken by the ship's meteorology department.

The reported relative ship's course was computed using the true course of the ship and the true direction of the sea swell. The swell direction was obtained from weather observations taken by the ship's meteorology department.

Some of the ship particulars for the GUAM as well as a computer fit of the underwater portion of the GUAM hull are presented in Table 2 and Figure 2, respectively. In addition, Appendix B presents some ship motion predictions for the GUAM. These predictions were made in order to assess systematically the effect of ship heading (relative to the waves) and ship speed on vertical velocities at various locations on the ship.

The aircraft operational procedural data consisted of observing how aircraft takeoffs and landings were timed relative to ship motions, and of noting and recording when and under what weather/sea conditions aircraft cancellations or delays occurred.

The audio visual data consisted of time correlating the electronic measurements with specific stages in the aircraft landing or takeoff cycle, and of noting and recording when unusual aircraft incidents occurred on the flight decks. Examples of such unusual incidents include skids, skid/bounces, as well as the crash of the LAMPS helicopter on the deck of the GUAM during the April-May 1973 at sea deployment.

DEFINITION OF AIRCRAFT EVENTS

Throughout the various at sea periods three distinct AV8 operating modes have been time correlated visually with ship motions. These are the STO's, or rolling short takeoffs, the VT's, or vertical takeoffs, and the VL's, or vertical landings.

Figure 3 illustrates the two types of aircraft takeoffs. For the STO, the time that the aircraft starts to roll at A is marked electrically

with a switch on the chart and magnetic tape. The switch is closed once the plane passes the ship bow at the nozzle rotation line, i.e., B. The NSRDC representative stationed in PRI-FLY visually observed the aircraft and operated the switch. For the VT, from the moment the aircraft lifts, i.e., the tires unload, until it reaches the level of the observer is marked by the switch. Generally, because of the Harriers much greater payload capacity with STO's rather than VT's, STO's were employed most frequently to takeoff.

Three landing modes have been observed to date. These landing modes are illustrated in Figure 4. It should be noted that for all types of aircraft landings and takeoffs the longitudinal axis of the aircraft was aligned to be parallel to the longitudinal axis of the ship. Only a few (less than 10) aircraft events were performed where there was an appreciable angle between the aircraft and ship longitudinal axes. These so called cross-axial landings (see Figure 5) have not been noted.

The normal vertical landing (see top of Figure 4) was used most frequently throughout the trials. For this type of landing, the aircraft crossed over the flight deck from the stern. Generally, the vertical clearance between the aircraft and the flight deck during the crossing or hovering over the deck was about 50 feet.

The TSL or translated starboard landing was generally used when other aircraft occupied the normal touchdown spot on the flight deck. During the TSL, the aircraft flies parallel to the ship until it is in proper longitudinal alignment with the deck landing spot. The pilot then moves his aircraft laterally across the flight deck at a height of about 50 feet

above the deck to this landing spot. Here, he hovers for a moment, searching for a ship motion lull, and then descends.

The third type of landing is a variation of the normal landing. It is of importance only insofar that this type of landing generally takes less than one motion cycle to complete. The waiting for the motion lull thus occurs over the water and not over the deck. The other types of landings generally take several motion cycles (over the flight deck) to complete. No particular distinction was made for any of the three types of landings in the analysis. All were treated similarly.

DATA ANALYSIS PROCEDURES AND OBJECTIVES

The objectives of the data analysis of the recorded ship motions are to

1. establish motion levels which limit aircraft operations
2. establish which particular component or group of components of ship motion produced aircraft event cancellation or delays
3. establish a measure of ship motion that accurately reflects the degree of motion induced difficulty in aircraft operations
4. relate this measure of ship motion from item 3 to a standard measure of ship motion .

Even though very long continuous ship motion measurements were made, the first analysis objective was obtained only for the landing and takeoff phases of the aircraft's operational cycle. This was accomplished by considering the landing and takeoff phases as being three separate

types of event, i.e., VL's, VT's and STO's. These events in turn were time correlated to ship motions and analyzed statistically.

Time correlation measurements which related ship motions to other phases of the aircraft operational cycle by means of similarly specific events within these phases were not made. Examples of such events include times required to perform routine pre or post flight maintenance, time required to move the aircraft from the hanger to the flight deck and time required to perform minor or major defined aircraft maintenance tasks. It is recommended that in future trials such quantitative time and motion studies be made for extended periods to define the maintenance degradation as a function of increasing ship motions.

The second analysis objective was attained by ordering the aircraft events by ship motion severity and by then employing correlation techniques to establish which component of ship motion produced event cancellation or delays.

The third analysis objective was attained by considering the physics of the aircraft landing or takeoff events to identify the ship motion measurement that reflects the motion induced difficulty in the aircraft event.

The fourth analysis objective was attained only for the short takeoff event. The measure of the motion induced difficulty in short takeoffs was compared to standard measures of ship motion which include the root mean square or RMS value of ship response and the highest ship response in 10 cycles.

DATA ORDERING PROCEDURE

To establish which component, or group of components, of ship motion produced the aircraft event cancellation (objective 2), the aircraft event related/ship motions were sorted in order of decreasing ship motion for specific components of this motion. Four distinct components or combinations thereof were considered. These were

1. pitch
2. roll
3. lateral acceleration
4. roll plus pitch

Details of the ordering procedure and related computer programs are described in reference 1.* It should also be noted that these same analysis procedures have been subsequently employed for ship/helicopter dynamic interface work in reference 2, and informally for AV8 operations aboard an LPD.

Two measures of ship motions were employed in the ordering procedure. These measures and the reasons for their selection are given in the following section.

It should be noted that the ordering by roll plus pitch (algebraic sum of roll and pitch) was made because the Harrier Squadron Commander indicated that this criterion was used by the squadron to establish the degree of motion induced difficulty in the aircraft operations. The physical reason for such a considered roll and pitch criterion is that the Harrier control power needed to compensate (maneuver) for various components

*A complete list of references is given on Page 104.

of ship motion is directly related to the total available engine (or lift) power. All control power is supplied directly by the engine. Thus, maneuvering power for compensation of large deck motions or high wind speeds is bled off from the power required for lift. It should be noted that 12 percent of all engine power is available for maneuvering.

Figure 6 presents a typical result from the order procedure. The vertical scale of the figure represents double amplitude roll in degrees, and the horizontal scale represents the ordered aircraft events. This graph presents the highest twenty aircraft events ordered according to a particular data channel--roll. That is, the first point represents the event that had the largest roll angle for the aircraft events obtained in the November and December 1972 and the January 1973 at sea periods with the GUAM. The second point represents the event which has the second highest roll, the third point represents the event which had the third highest roll, etc. These events are completely time independent in the sense that the first event may have occurred in January, the second event may have occurred in November, the third event may have occurred at a different time in January than the first event, etc. Notice that the remaining hundreds of aircraft events have not been shown in the interest of brevity.

AIRCRAFT/SHIP MOTION MEASURES

Two measures of ship motions that relate to the degree of aircraft event difficulty were considered. These measures are defined in Figures 7 and 8. The first consists of the largest double amplitude (or

Max-Min) that occurred within a given event (see Figure 7); and the second measure consists of the most important value of the instantaneous ship response for the type of aircraft event considered. Figure 7 illustrates both the double amplitude measure and the instantaneous measure. It should be noted that the double amplitude may be equal to, or greater, or occasionally less than, the instantaneous value. This latter possibility is demonstrated in Figure 8. It can be seen here that the instantaneous value is about twice the double amplitude for the second event.

The instantaneous value is measured relative to the reference zero, see Figure 8. This reference zero in turn is established in the harbor and relates to the ship's bubbles and the ship's gyrocompass reference.

Notice also that the double amplitude refers to ship motions at a different time than is the case for the instantaneous value. It is assumed that the double amplitude represents the motion value to which a pilot will respond with deliberate aircraft control changes. For example, if the double amplitude occurred during a takeoff, and if this double amplitude were to represent, say, roll angle or lateral acceleration, the pilot would apply sufficient directional control to compensate for these ship motion induced aircraft disturbing forces. Thus, the maximum double amplitude in an event is regarded as being a measure of degree of difficulty due to ship motion encountered by the pilot in a particular aircraft event.

It is recommended that the validity of this assumption be investigated by correlating the pilot control position movements with these maximum double amplitudes in an aircraft event. Simultaneous ship motion

and aircraft control position measurements are required.

Thus the first measure of ship motion relates directly back to the double amplitude values given to and used by the ship during the at sea evaluations. It also relates to the degree of motion induced difficulty for a particular event.

The second measure of ship motion on the other hand, i.e., the instantaneous value at a critical point in the aircraft event, is the one which the pilot may have more difficulty in controlling. Yet this instantaneous value may be critical for the physical considerations involved in the successful completion of the aircraft event. To illustrate this point, consider a VL. It is clear that the instantaneous value of ship motions at the time that the aircraft is in the process of becoming fully supported by the ship may be more meaningful than the extreme double amplitude in the event. Lateral skids, as well as skid/bounces, occur during this crucial time in the aircraft landing. Due to rather limited lateral freedom, lateral skids are regarded as precursors of serious aircraft difficulties. These then are the reasons for the choice of the two ship motion measures by which the data is sorted in order of decreasing ship response.

LULL ANALYSIS

TIMING AIRCRAFT EVENTS RELATIVE TO SHIP MOTIONS

It was noted that the operators do not perform critical aircraft operations in a random manner with respect to ship motions. In fact, the operators attempt to time critical aircraft operations to occur during lulls in ship motions. A lull in ship motion means a series of successive, relatively

small motion cycles. This timing of aircraft operations appeared to occur whenever ship responses were high enough to affect operations, i.e., significant motion greater than one or two degrees. Critical aircraft operations included the launches, landings, movement of aircraft on flight or hangar deck, as well as the movement of the aircraft on and off the elevators.

In the case of a STO for example, the operator (LSE) tries to launch the aircraft during a lull, i.e., a series of small successive motion cycles (measured by double amplitude). In addition, he tries to time the start of forward movement of the aircraft such that it will reach the nozzle rotation line at the bow, when the bow is up rather than down (see Figure 9). Clearly the LSE attempts to predict an instantaneous value of ship motion that is favorable for a takeoff. Obviously a take-off with the ship in the attitude of Figure 9 could result in a lost aircraft, especially when a marginal* lift STO occurs. Thus the very serious consequences of a marginal vertical lift STO during a bow down position make the successful prediction of the bow attitude extremely important.

In case of VL's the LSO, a squadron pilot, gives the final clearance to land. The LSO, stationed in PRI-FLY, is of course equally sensitive to the motions of the ship as is the LSE during STO's. Consequently, after the aircraft has been brought over the deck to the selected landing spot and the pilot hovers over this spot awaiting the final descent sign, the LSO attempts to time this signal so that the actual landing will occur during a lull in ship motions. In other words

*Rate of climb at instant of takeoff from bow very small

the LSO gives the descent signal based on his judgement or prediction of the ship motion that will exist when the aircraft touches the deck.

In passing, it should be noted that during the aircraft handling/moving portion of the operation cycle, the operators time their movements to occur in a given half cycle of motion. That is, they move the aircraft with a tractor when the deck angle is inclined to have gravity move the aircraft, i.e., they do not try to push/pull the aircraft uphill. Thus it may be seen that the operators try to time the aircraft events using double amplitude, instantaneous values, as well as half cycles of deck motions.

LULL ANALYSIS OBJECTIVE AND PROCEDURE

It was considered essential for the understanding of the ship/aircraft interface problem to relate the operator's success in performing critical aircraft operations during ship motion lulls to some standard measures of ship motions such as significant or average ship motions. For this reason, therefore, what is called a "lull analysis" was undertaken. The objective of the lull analysis is to establish a realistic design/operator value for use in the ship/aircraft interface design.

Two basic analysis procedures were employed. The first attempts to establish how successfully a lull was found by comparing the event motion double amplitude with the highest double amplitude within the 10 cycles preceding and following the aircraft event. The second compares the event motion double amplitude with essentially the standard deviation of ship motions that occurred during a one half hour time period within which the aircraft event occurred.

EXAMPLE OF SHIP MOTION LULL

Figure 10 demonstrates for an actual event, the operator's attempt to time the event so that it will fall within a lull of ship motion. Roll motion is particularly marked with an obvious lull, although the pitch motion also has a lull. The vertical acceleration at the touchdown point, on the other hand, shows no clean motion lull. The consequence of missing a motion lull may be quite serious. For roll, missing the lull may result in increases in ship roll during the aircraft event by factors of two to ten. As a example of a missed lull, note the worst roll case realized during the November, December, January segments of the trials illustrated in Figure 11. For pitch, increases on the order of a factor of two may be expected.

MEASURE OF SUCCESS IN FINDING SHIP MOTION LULL

To measure the degree of success which the operators have in performing the actual aircraft operations during lulls in ship motions, the highest double amplitude in ten cycles of motions preceding and following the actual aircraft event is considered. This ten cycle before and after criterion was adopted for two reasons. The first relates to the hovering capability of the Harrier aircraft. That is, the Harrier can hover over the deck for about 20 motion cycles or correspondingly somewhat more than two minutes. The second reason for using this measure of success is that the highest value in 10 cycles of ship motion relates statistically to other standard measures of ship motions (such as RMS) in irregular seas (see Table 1).

As may be noted from the case of the roll channel in Figure 10, the highest double amplitude within ten cycles before the aircraft event is the 10th cycle. This is denoted in Figure 10 by a filled in circle. Similarly the highest double amplitude within ten cycles after the event, denoted by an open circle, actually occurs six cycles after the event.

These highest double amplitudes in ten cycles before and after the event are demonstrated for STO's ordered by double amplitude of roll in Figure 12. The vertical scale on the graph is double amplitude in degrees, and the horizontal scale represents the ordered events. The highest values, irrespective of whether they occurred before (•) or after (o) the event, are connected by a line. The same is true for the lowest values. When the area between these two lines lies above the ordered double amplitude line, the operators were successful in operating in a lull. The higher the shaded area lies above the ordered double amplitude line, the greater the degree of success. Similarly, when the shaded area is below the double amplitude line, the operators were unsuccessful in landing during a lull. The reason that they may have been unsuccessful in landing during the lull may be either that there was no discernible lull in ship motion (see vertical accelerations in Figure 10), or that they just missed it for any one of a series of operational reasons (see Figure 11, worst roll).

In general, the data of Figure 12 demonstrates that for STO's and roll, the operators are indeed successful in performing the operations during a lull. On the other hand, failures to time events so as to operate

during a lull are also shown. The first event of Figure 12 clearly represents such a case, and a similar failure is illustrated by the worst roll case of Figure 11.

Typical successes and failures in performing the aircraft operations during ship motion lulls are shown for STO's and VL's in Figure 13 in the same general format as for Figure 12. Figure 11 presents similar data in time history format. The aircraft event data for both STO's and VL's is ordered by double amplitudes of roll and pitch in Figure 11. Again the vertical axes represent double amplitude roll or pitch in degrees, and the horizontal axes represent the ordered events. It may be noted here that this example covers only the November 1972, December 1972 and January 1973 at sea trials. This same type of analysis has not been performed for the remaining trial measurements. This analysis was merely intended to indicate how aircraft operations can be related to some standard measures of ship motion.

SOME LULL ANALYSIS CONCLUSIONS

In examining Figure 13 it is noteworthy that

1. there appear to be more successes for roll than for pitch, indicating that locating a lull in roll is easier than locating a lull in pitch
2. there appear to be more roll successes for STO's than VL's, indicating that locating lulls is more difficult for longer events (VL's) than for shorter events (STO's)

3. STO's ordered by roll tend to occur at ship motion values less than, or at most no greater than, the highest values in either 10 or 20 cycles

4. the highest values of STO's ordered by pitch, on the other hand, tend to occur at ship motion values that are about 1.5 times as great as the highest values in 20 cycles, see for examples events one and three. These STO's thus tend to occur at ship motion values equal to or less than the highest values in about 1000 ship motion cycles. Thus STO's may be adversely affected even by low values of pitch

5. the highest values of VL's ordered by roll and by pitch both tend to occur at ship motion values of about 1.2 times greater than the highest values in 20 cycles when only the highest 10 events for each are considered. The VL's thus tend to occur at ship motion values equal to or less than the highest values in about 100 ship motion cycles

RELATION BETWEEN AIRCRAFT OPERATION DIFFICULTY AND STANDARD SHIP MOTION MEASURES

An alternative procedure to relate the aircraft event motions to standard measures of ship motion was considered. This procedure is not based on identifying specific ship motion lulls. Instead, it is based on relating the aircraft event motions to the standard deviation of the ship motions. This standard measure of ship motions is derived

from a power spectrum analysis of the motions that occurred within the same 20 to 30 minute time period within which the aircraft event occurred It is to be noted, however, that in order to get statistically valid ship motion values (standard deviation or RMS) ship speed and heading have to be constant for the 20 to 30 minute interval in which the aircraft event occurred. Thus for events 5 and 13 of Figure 14 a power spectrum analysis could not be made because the ship did not maintain its course and heading for a sufficiently long time.

The results of the power spectrum analysis for the roll STO case are shown as a dashed line in Figure 14. The vertical axis of this figure represents roll in degrees and the horizontal axis represents the events ordered according to decreasing double amplitudes of roll. Again, the solid line represents the ordered aircraft event double amplitudes and the dashed line represents a standard measure of ship motion derived from the power spectrum analysis, namely the $\sqrt{Q_0}$ value. This value is defined to be equal to the product of $\sqrt{2}$ and the RHS roll angle. The constants of Table 1 further relate the results represented by the dashed line, i.e., $\sqrt{Q_0}$, to other statistical measures of ship motion such as the average motions or the highest expected motions in N cycles.

Consider the highest motion levels in the present data sample in order to develop a rough relationship between standard ship motion measures and aircraft event motions, i.e., the levels of ship motions at which pilots tend to land or take off may be established. A comparison for the first seven events between the aircraft event roll* and

Highest roll within aircraft event, see Figures 7 and 8.

the associated graphed standard ship motions measure $\sqrt{2}$. RMS or $\sqrt{Q_0}$ indicates that the events occur at ship roll levels that vary from about 1.0 · RMS to 2.5 · RMS. Generally, at these higher motion levels, $\sqrt{2}$ · RMS or $\sqrt{Q_0}$ provides a reasonably good fit to the aircraft event data line. The event with the highest roll however obviously does not fit this $\sqrt{Q_0}$ relation. In fact the highest roll aircraft event appears to have occurred at a motion level that corresponds almost to the average double amplitude. Nevertheless, as a rough, general guide it is tentatively concluded on the basis of the limited data of Figure 14 that operators tend to perform the STO's at the $\sqrt{Q_0}$ value of roll.

It must be noted, however, that the $\sqrt{Q_0}$ value measure is only strictly valid for STO's ordered by roll. It is concluded that for future ship/aircraft interface design, similar data fits should be made for the data ordered by pitch and roll for all GUAM VL's and STO's for which the data was collected. It is expected that VL's would tend to occur at higher values of roll than $\sqrt{Q_0}$ since VL's are of longer duration than STO's. Until similar data fits are performed for STO's during pitch and VL's during roll and pitch, the highest expected double amplitudes in 1000 cycles and 100 cycles, respectively, might be used to define the ship motion levels at which aircraft landings and takeoffs tend to occur. This conclusion is based on the results of Figure 13. It is also concluded that this general approach to ship/aircraft interface analysis would be equally valid for helicopter/ship interface investigations.

CORRELATION BETWEEN SHIP MOTION AND AIRCRAFT EVENTS

ANALYSIS OBJECTIVES AND PROCEDURES

The objective of the following analysis is to establish the motion levels at which aircraft operations were adversely affected by ship motions, and to establish which component of the ship motions produced the difficulties. It was also regarded essential to record the relative importance of ship motions as one of a series of causes in delays or cancellations of aircraft operations.

The first objective was examined in one fashion in the Lull Analysis section of this report. A second procedure is employed in the present section. This procedure essentially consists of collating the ship motions and operating conditions that existed when Harrier air operations were adversely affected by ship motions. While collating these motion and operating conditions, it becomes clear that there is no single cause of delays or cancellations in aircraft operations.

The second objective which established the component of ship motions that produce operational difficulties is obtained by sorting the ship motions associated with particular aircraft events in order of decreasing ship motion levels.

The troublesome motion component may be identified by noting the relative position of the majority of cancellations, delays, or precursors of aircraft difficulties in the ordered sequence of events for that component. If, for example, the majority of cancellations, etc., occur at or near the top of the ordered sequence, then it may be assumed that

the component in question is associated with the source of these cancellations. If, on the other hand, the cancellation delays or skid-bounces occur at random throughout the ordered sequence, it may be assumed that the component is not directly associated with the cause of the cancellations. It was regarded important to identify the component of ship motion that produced the most difficulties in the aircraft operations because some components of ship motion, such as roll are more readily influenced by hull design changes than others, such as pitch or heave. In addition, since these measurements and observations were made as part of the Sea Control Ship design it was considered necessary to note specifically how the motions interfered with the aircraft operations, and to record various operational procedures which potentially impact the ship design.

It was noted that the aircraft operation cancellations are produced by the operator's judgment that "the motion levels are too high." In addition, it was considered that this judgment was affected by

1. the levels of all perceived motion components
2. the occurrence of precursors of ship motion induced problems such as skids and bounces
3. other operational causes

In addition, it was noted that the operators did not necessarily indicate to the NSRDC staff which component of ship motion or other factors entered into an aircraft operations cancellation. It was decided, therefore, to employ statistical correlation procedures to identify the ship motion component which produced aircraft operational difficulties.

DATA FORMAT EXPLANATION

Figures 15 through 19 are intended to explain the general format of the data. These figures were made from the November, December 1972, and January 1973 data which was ordered by hand to develop the computer data reduction procedure.

Figure 15 presents a summary of the ordered ship motions for all three types of aircraft events with the horizontal rows of graphs representing the data for the three types of events, i.e., VL's, VT's and STO's. The data was ordered by decreasing event double amplitudes of pitch, roll, and lateral acceleration. The first vertical column of graphs represents the data ordered by pitch, whereas the second and third columns represent the data ordered by roll and lateral acceleration.

It should be noted that the events in the individual graphs are unique. That is for example, event 1 for STO ordered by roll may be a different event than event 1 for VL ordered by roll, pitch, etc.

Figure 15 also presents the largest event double amplitude for each ordered sequence. For example, the largest event double amplitude for roll that occurred during the November, December, January trials is 7.3 degrees for VL's, 5.0 degrees for STO's, and only 0.9 degrees for VT's.

Precursors of aircraft operational difficulties are denoted in Figure 15 by single ended arrows whereas actual delays or cancellations of aircraft events are denoted by double ended arrows. These delays and cancellations are further defined in the following section.

The data for all trials corresponding to the November, December, January data of Figure 15 is presented in Figures 20 through 23.

Figure 16 presents in histogram format the time durations of the aircraft events of Figure 15. Again the basic format of the figure is similar to that of Figure 15. Time duration results for all trials corresponding to Figure 16 is given in a separate section. Discussions of the results of the data of Figure 16 is also presented in that section.

Figures 17, 18, and 19 present for STO's, VL's, and VT's respectively the double amplitude aircraft event ship motions ordered by pitch*, roll, and lateral accelerations. These figures also present for each ordered event the associated ship motions, environmental conditions of wind and seas, and aircraft status such as the aircraft location** relative to ship, aircraft weight, time duration of the events, etc.

The results for all trials corresponding to Figures 17, 18, and 19 are given in Figure 24. However, since VT's are not of major operational importance for Harriers operating from sea control type ships no VT data summary for all trials is given.

Table 3 and 4 present summaries of conditions that relate to aircraft event cancellations or delays. These cancellations and delays due to ship motions are indicated by double ended arrows in Figures 20 through 24. The numbers associated with these arrows refer to the cancellations or delays as listed in Table 4.

---

* For pitch ordered data, for example, associated ship motions consist of vertical bow acceleration, vertical and lateral acceleration at the touchdown point/most frequent starting point, and roll.

** Location of aircraft at the start of the event for takeoffs and at the end of the event for landings.

DEFINITION OF AIRCRAFT OPERATION CANCELLATIONS

Returning now to Figure 15, notice that double ended arrows are shown for the VL's and STO's. These denote aircraft operation cancellation. An event is defined as a cancellation event if the aircraft operations were cancelled immediately after the evolution occurred. That is, a cancellation event is defined to have occurred in the last Harrier take-off/landing evolution prior to the cancellation, provided that evolution occurred immediately before the cancellation. A delay event is similarly defined as occurring in the evolution immediately before, or (in the case of a landing) the evolution containing the delay. Before and immediate implies in the same statistical period, i.e., statistically stationary wind and sea conditions, or from one to about three hours. It is therefore possible to have two or more events associated with the same delay or cancellation if two or more Harriers were involved in the evolution being analyzed. For those cancellations in which no events occurred immediately before the cancellation, no data are shown.

It should be noted that the precursor of ship motion induced aircraft problems, namely skids, and skid/bounces occur at motion values below the cancellation values (Figure 15). This, in turn, leads to the tentative conclusion that ship motions can result in aircraft operational difficulties at very low motion values but that the aircraft operations can be performed at much greater values than the ones which first produce skids and skid bounces.

QUALITY OF OBSERVED HARRIER/SCS MOTION LIMITS

It should be noted that there were relatively few people involved in the critical stages of the aircraft operations studies. A tabulation of this number is:

Captain	1
Air Department Head	2
Harrier LSE	2
Harrier LSO	9 to 12
Harrier Pilots	9 to 12

While it is recognized that these people may have been quite cautious during the initial stages of the Harrier operations, the impression was gained that by the time the April-May 1973 trials occurred, no unnecessary caution was used in the deployment of the aircraft. It is therefore concluded that the observed ship motion limits on aircraft launch/retrieval operations represent realistic upper limits of the aircraft/ship system under present conditions.

SUMMARY OF AIRCRAFT OPERATION CANCELLATIONS

Before continuing the discussion on the results and implications that may be inferred from the data of the various figures, a brief summary table of aircraft cancellations due to all causes is presented in Table 3. It is to be noted that initially the NSRDC observers were tasked only to record the cancellations due to ship motions of Harrier operations. Consequently, the air operation cancellations/delays due to all causes in Table 3 do not necessarily represent all of the delays/cancellations

that occurred. There may be another two or three Harrier delays/ cancellations due to various causes which were not identified from the trial notebooks or which were not even recorded therein.

Helicopter delays/cancellations were not tabulated by the NSRDC observers. There were quite a few helicopter operational delays due to a variety of nonmotion causes. These delays, however, were not recorded because they were of no importance to the observers at the time of the operations. It should however be noted that generally helicopter operations were cancelled almost immediately following the cancellation of Harrier operations. Thus, there appeared to be no substantial difference in the motion/wind, etc. conditions that interfered with and/or cancelled either Harrier or helicopter operations. However, since the helicopters employed very restrictive limiting wind envelopes during the trials, the relative operability of Harriers and helicopters cannot be inferred from the available data.

The inability of the GUAM to maintain its appropriate position relative to a moving convoy progressing at speeds within four or five knots of the GUAM's top speed is a source of aircraft operation cancellations or delay not explicitly brought out in Table 3. Again, since this type of data was neither easily obtained from the operators nor did it appear at the time of the deployments to be absolutely essential, these convoy position related delays or cancellations were noted only during the latter stages in the deployments. It is noted in this context that if the Sea Control Ship's speed advantage over the convoy is as low as four or five knots, either the aircraft launch/retrieval cap-

abilities of the ship or conversely its convoy position-keeping capability will be degraded.

As a result of the above factors Table 3 does not contain all of the cancellations or delays. The data is presented in order to provide an estimate of the relative frequency and thus importance of ship motions as a source of Harrier operation cancellations. It may be seen that of the 30 delays/cancellations, 15 were due to various weather factors, 9 were due to miscellaneous ship/aircraft operational status causes, and 6 were primarily to ship motions. When the cancellations due to weather and other causes not noted by NSRDC are considered, it is concluded that weather rather than ship motion is the predominant, direct cause of aircraft operation cancellation.

Table 4 presents, in somewhat greater detail than Table 3 the individual times when motions were the primary source of difficulties with Harrier air operations. These motion-related difficulties produced either delays or cancellations in the operations. Essentially, these difficulties occurred only on five different days throughout the various deployments. It must be noted, in fact, that these events occurred only during the last three (out of fourteen*) deployemnts of the GUAM, i.e., during the winter deployments.

The data is presented in four groups of columns. The first group refers to the trials particulars and identifies the individual delays or cancellations with a unique number as noted in Figures 20-24.

*NSRDC participated in 14 at-sea deployments of the GUAM operating as the ISCS.

Ship, wind, and sea conditions for the events are presented in the second group and corresponding ship motions and amplifying comments are given in the third and fourth groups respectively.

It must be noted that the ship course and speed were constant during the 30 minute time duration for which statistical ship motion levels are given in terms of $\sqrt{Q_0}$ values (refer to Table 1 for the statistical constants that relate these response levels to other desirable response statistics). Thus the ship response data presented was collected for stationary ship operating conditions over a one-half hour interval. This interval, in turn, generally contained a Harrier landing or takeoff event. Relative wind was recorded from the repeaters in PRI-FLY at 5 to 10 minute intervals during the times Harrier-helicopter events occurred. Surface wind and sea data, on the other hand, represent data samples taken at one hour intervals. As a result, therefore, it is not possible to infer with precision the surface wind and direction at the exact time when a Harrier event was delayed or cancelled due to ship motions.

The directions associated with ship course, surface wind, and swell are all referenced to the earth's true north as noted on the ship's magnetic compass. Both surface wind and swell come from the tabulated direction, whereas the ship course proceeds towards the tabulated direction. Relative wind over the deck, or course, is referenced to the centerline of the ship, as is the ship's relative heading to the swell. The relative heading to the swell is 180 degrees when the ship heads directly into the swell, is equal to 90 degrees when the swell approaches from the port beam, and is equal to 0 degrees when the swell approaches direct-

ly from the stern. The column of data labeled "Type Sea" presents the predominant direction of the sea relative to the direction* of advance of the ship. Thus, for delay event 1 on the 14th of January, the predominant waves approach the ship 55 degrees off the port bow.

Several additional comments are made concerning the data presented in Table 4. It is noted that although the operators attributed the cancellations or delays primarily to motions, the wind over the deck is near or above the forty knot limit established for Harrier vertical landings in eleven of the fifteen cases encountered. In eight of the eleven high WOD cases, ship speed was reduced below the nominal convoy speed to reduce the WOD to an acceptable level.

In examining the sea conditions that occurred at the time of the cancellation, it is noted that swell height is equal to or greater than the wind driven sea wave height. It may be concluded therefore that the wind will affect air operations to the same or greater extent than the waves it produces.

Cancellation 2 of Table 4 represents a unique event within the trials. A Harrier fly-on from the beach was landed during a cancellation period caused by ship motions. This landing occurred without incident; however, the double amplitude pitch motion during the event was the seventh largest recorded during the trials (see Figure 24).

Referring to the tabulated $\sqrt{Q_0}$ motions notice that air operations are delayed generally when $\sqrt{Q_0}$ pitch attains values ranging between 1.2

*Using the ship to wave heading convention employed by the operators.

and 1.5 degrees and are generally cancelled when $\sqrt{Q_0}$ pitch attains values between 1.5 and 2.0 degrees. When $\sqrt{Q_0}$ pitch motions exceed 2.0 degrees no Harrier operations occur. It should be noted however, that the inability to predict the ships bow attitude can produce aircraft operational delays or cancellations at $\sqrt{Q_0}$ pitch values considerably less than 1.2 degrees. See Table 1 for conversions of $\sqrt{Q_0}$ values to other standard motion measures.

TIME DURATIONS OF AIRCRAFT EVENTS

Figure 16 presents the event duration times for all three types of aircraft events. These times are for the events shown in Figure 15. The duration times for the highest 20 events for STO ordered by pitch, for example, are represented by two time intervals. Eight of these events are between 4 and 6 seconds long and twelve between 6 and 8 seconds long. Again, as was the case for the previous figure, the vertical column of graphs under pitch represent the aircraft events for VL's, VT's, and STO's ordered by pitch. The VL's took from about eight to 48 seconds to accomplish. The VT's on the other hand took only from about 2 to 12 seconds, being in many cases the shortest aircraft events. The STO's on the other hand never appeared to take more than 8 seconds to complete.

A review of the time durations for all VL's performed during the trials indicated that the average time duration for a VL was equal to 17.5 seconds. The average of the longest 5 percent of the VL's was 35.9 seconds, and the average of the remaining 95 percent of the VL's was 16.7 seconds. Very few (about 2.5 percent) of the VL's were accomplished in

less than 7 seconds. The very short VL time durations were found to be the result of the deliberate use of the alternate VL procedure (see Figure 4).

The average time duration for all VT's was 4.4 seconds. The average of the longest 5 percent of the VT's was 17 seconds and the average of the remaining 95 percent of VT's was 3.63 seconds.

The average time duration for all STO's was 5.8 seconds, whereas the average of the longest 5 percent of the STO's was 10.1 seconds, and the average of the remaining 95 percent of the STO's was 5.6 seconds.

It is interesting to note that all three types of aircraft events can be accomplished generally within a single complete pitch cycle if the alternate VL procedure were used. Similarly, it is equally interesting to note that VT's are a quicker method for taking off than the STO's.

The fact that all three types of aircraft events can be accomplished within a given ship motion cycle suggest that with existing ship motion technology the aircraft could be "timed" to pass through a critical stage in the event when the motions are least likely to produce skids, bounces or relative yaw between ship and aircraft.

INFLUENCE OF EXPOSURE TIME ON OBSERVED EXTREME VALUES OF SHIP MOTIONS DURING AIRCRAFT EVENT

Generally, the ship motions were less during the VT's than during the VL's and STO's. The reason for this is two-fold. Firstly, the VT's were performed generally in lower seas* than the VL's and STO's. Secondly, the time duration for a VT is generally shorter than for other

*This is during the initial at sea periods of the ISCS GUAM when operations were performed near the North/South Carolina shore.

events. This reduced exposure time to the sea of the aircraft in a critical stage in its operation reduces the possibility of performing the event during a large ship motion. Both the data from the November, December, January trials (Figure 15) as well as the summary data for all trials (Figure 20), clearly support the above rule. For pitch for example, the long VL's have almost twice as large an extreme double amplitude than for the shorter STO's or VT's (5.1^{0} VL versus 2.7^{0} STO versus 1.2^{0} VT) (Figure 15). It was noted that some pilots appeared to be aware of this rule, i.e., reducing aircraft event duration over the deck of the ship reduces probability of performing a critical part of the aircraft evolution in large motions.

CORRELATION OF SHIP MOTIONS, AIRCRAFT STATUS, AND ENVIRONMENTAL CONDITIONS

Figures 17 through 24 present all of the available ship motion, aircraft condition, and sea condition data for the Harrier deployments aboard the GUAM as the Interim Sea Control Ship. The data includes the locations at which the aircraft events were either started (STO) or ended (VL) as well as the gross weight of the aircraft.

Figure 17 presents the STO data for the November 1972, December 1972, and January 1973 trials ordered by pitch, roll, and lateral acceleration. Comparable data for VL's and VT's are given in Figures 18 and 19.

As was the case for Figure 15, the double ended arrows in the graphs marks the same cancellation in January 1973. Time histories of these STO and VL cancellations are illustrated in Figure 11.

It should be noted in Figures 17, 18 and 19 that the ordered motion columns have all the events corresponding to one another. Thus, the first event in the pitch ordered by pitch graph has its corresponding bow acceleration plotted as the first value in the bow acceleration graph located directly below. The corresponding wind direction and speed relative to the ship is plotted as the first value in the fifth graph (from the top). The gross weight of the aircraft and the location on the ship where the aircraft event occurred is similarly presented in the seventh and eighth graphs from the top.

IMPORTANCE OF WIND ON AIR OPERATIONS

Aircraft launch and recovery operations were performed only when the wind over the deck (WOD) was within ± 20 degrees of coming from directly ahead (see Figures 17, 18, 19, and 24 WOD data). Thus, the operators adjusted the speed and/or the heading of the ship, taking into account the true direction and velocity of the wind, to force the resulting relative WOD to come from within the relatively narrow ± 20-degree sector about the bow of the ship. The reason for this restrictive choice in WOD directions during aircraft operations is, of course, associated with the allowable relative wind envelope for the aircraft.

It is apparent from the relative ship heading data of Figures 17, 18, 19, and 24 that the ship was driven into the seas at a variety of different headings ranging from head to quartering seas. True head sea operations, however were quite rare even when only the pitch ordered data of Figure 24 is considered.

The surface wind and ship heading relative to the predominant sea data including the Harrier cancellation/delay of ..ble 4 indicates that the wind and predominant seas do not come from the same direction. For example, for more than half of the ship motion induced Harrier air operation delays or cancellations the surface wind came from a direction that was 30 degrees or more away from the direction of the predominant sea. The cross wind limitations specified in the AV8-A Shipboard Operating Bulletin (see reference 3) should be consulted along with the data of Figures 17, 18, 19, and 24 in order to determine the operational implications of this finding.

It is concluded from the results of Figures 17, 18, 19, and 24 that for the Harrier air operations wind direction rather than sea or swell direction, or even a preestablished operational course dictated the ship heading. It must also be noted that the same operational procedure was generally followed when helicopters were launched or recovered. It is considered that the use of these operational constraints for the H-3 helicopters flying from an LPH was not fully justified since these aircraft can perform cross wind landings. In other words, the NATOP's wind envelope limits for the H-3 operating from the LPH appear to be unnecessarily restrictive.

RELATIVE IMPORTANCE OF SWELL AND WIND SEAS

The following comments concern the type of wave systems that are of importance in terms of interfering with aircraft operations. It is noted in Figures 17, 18, 19, and 24 that generally swell rather than the local wind driven sea was the largest component of the encountered seas.

It should be recalled that a ship of the size of the GUAM has larger per unit wave height response at swell frequencies than at local wind wave frequencies. It is concluded on the basis of these factors, therefore, that swell is much more important for aircraft operations than the locally operated, short crested seas. Swells produce the ship motions which in turn result in delays or cancellations in aircraft operations. Local wind waves on the other hand do not generally interfere with aircraft operations except occasionally in generating spray.

It is important to note therefore that the ship motions which produce operational difficulties in the aircraft launch/retrieval cycle are not associated directly with the wind. In fact, since wind direction and swell direction are independent, either one or the other or an unfavorable combination of both may produce aircraft operation delays. Changes* in wind direction and speed over the 2 to 3 hour duration of an aircraft mission thus is far more likely to induce difficulties in the aircraft recovery operation than would wave growth due to the local action of the wind.** Similarly, the arrival of new swell wave trains from distant storms is also considered to be more important than wave growth due to wind action.

All of the conclusions relating to the relative importance of sea and swell, however, are based on the ability of the GUAM's wave height observers to distinguish between sea and swell.

---

*Such as the changes that occur with the arrival of a weather front with its associated highly variable wind gusts and/or precipitation squalls.

**These general conclusions are valid unless the predominant wind direction is aligned sufficiently closely with the direction of the swell to produce a rapid growth rate in the swell.

SEA STATES ENCOUNTERED DURING GUAM TRIALS

The highest encountered sea state was a Sea State 5*, which contained a 10 foot swell. Between one-half to one-third of the sea conditions for the highest 30 events (VL, STO) sorted by pitch (Figure 24) occurred in State 5 seas. The majority of the remaining events occurred in State 3 to 4 seas.

In examining the sea conditions for which the highest 20 or 30 aircraft events ordered by pitch or roll occurred (Figures 17, 18, 19 and 24), it is noteworthy that of the three types of events the longest events, i.e., VL's, tend to occur in the higher sea conditions. Since both VL's and STO's were conducted under the same actual sea conditions, this suggests that the longer VL's are more likely to occur with large ship motions in a given sea state than is the case for the shorter STO's. Again, this result points towards the desirability of making the aircraft event time over the deck as short as possible.

BI-DIRECTIONAL TAKEOFF CAPABILITY FOR SEA CONTROL SHIP

Since the aircraft takeoff (and land) into the wind, the capability of the Sea Control Ship (as far as Harrier operations are concerned) can be significantly improved, i.e., 29 additional days of ship air operations per year in the North Atlantic, if aircraft can also takeoff from bow to stern rather than just from stern to bow as is conventional for catapult equipped aircraft carriers. Both the maximum wind speed at which Harrier operations can be performed and the per-

---

*As defined in Table 1.

centage of time that the SCS needs to deviate from its convoy course can be improved in this fashion. These topics are discussed in detail in Appendix C.

SHIP MOTION COMPONENT THAT PRODUCES AIRCRAFT OPERATION CANCELLATIONS

Figures 20 and 21 were prepared to clearly identify the ship motion component that produces cancellations or difficulties in the aircraft operations. The aircraft events ordered by both double amplitudes and instantaneous values of ship motion are shown. Again the definition of these motion measures are given in Figures 7 and 8 and were appropriately discussed earlier. The double amplitudes are shown by the solid lines in Figures 20 and 21, and the instantaneous values are shown as black circles (o). Figure 20 presents the data ordered by double amplitudes and Figure 21 presents the data ordered by instantaneous values.

The vertical scale of the graphs represents degrees with the zero reference sketched in by the broken line. The horizontal scale of the graphs represents the independent events as was the case for the motion summary, Figure 15.

The cancellations, previously defined, as well as the aircraft operation delays, are shown by double ended arrows. These are related to cancellations and delays listed in Table 4 by the associated numbers. Also, as was the case for Figure 15, the maximum values of the ordered double amplitudes are given.

Returning to Figure 15, note that for both VL's and STO's, the cancellation and the skids and bounces occur within the top 20 events when ordered either by roll, pitch, or by lateral acceleration. Thus, on the basis of this data, it is not possible to infer which ship motion component produces the difficulties in aircraft launch/recovery operations. However, when Figure 20, which presents a summary of all trials, is examined it becomes quite clear that a cluster of cancellations and delays occur near the top of the ordered sequence for pitch. Neither the roll, nor the roll plus pitch ordered sequence contains a similar cluster of cancellations and delays. Thus, the data of Figure 20 strongly suggests that pitch is the ship motion component that produces difficulties in the launch and recovery portion of the aircraft operations. The ordered instantaneous values of Figure 21 confirm the fact that pitch is the troublesome component of ship motion for VL's and STO's.

It is also noted that the clustering of cancellations and delays occur primarily in the VL's rather than the STO's suggesting that the landings are more seriously affected by pitch motions than are the STO's. In order words, VL's are more sensitive to ship motions than STO's.

EFFECT OF PITCH AND BOW ATTITUDE ON AIRCRAFT OPERATIONS

Figure 23 was prepared to compare the instantaneous ship motion values (black circles) with the event double amplitudes (solid lines) and to illustrate the bow attitude at which the Harriers left the deck during the STO's.

The dashed horizontal line in the figure shows the at rest attitude of the GUAM during the various trials. That is, the GUAM generally operated with a one degree bow up trim. It is interesting to note that the operators were not always successful in launching the aircraft with the ship in the bow up attitude when the Harrier crossed over the bow (stated launch procedure). The ability to accurately predict the bow attitude is, however, extremely important since the inability to predict this was associated with fully one third of the recorded Harrier delays or cancellations. For example, the inability to predict the bow attitude during two successive Harrier takeoffs resulted in a cancellation in the Harrier launch operations. It should be noted that the inability to predict the bow up attitude can result in delays or cancellations even in seas which produce very little pitch. See Table 4 cancellation number 8 and the two STO's in Figures 22 and 23 that are shown as occurring in a bow down attitude.

ROLL STABILIZATION GOAL FOR THE SEA CONTROL SHIP

Figure 22 was prepared to compare the roll motion levels at which the VL's and STO's occurred with the Roll Stabilization Goal selected for the design of the Sea Control Ship. The stabilization goal was selected by the Naval Ship Engineering Center (NAVSEC) and the Naval Ship Systems Command.

The roll stabilization goal is equal to 16 degrees double amplitude, i.e., the highest expected double amplitude in 100 cycles of roll is 16 degrees. Since STO's are generally performed at roll motion levels corresponding to $\sqrt{Q_0}$ (note $\sqrt{Q_0} = \sqrt{2} \cdot$ RMS and see Figure 14 and Table 1) and the 16-degree double amplitude roll goal is equal to 4.29 $\sqrt{Q_0}$, the roll stabiliza-

tion goal corresponds to a $\sqrt{\sigma_0}$ value equal to 16/4.29 or 3.73 degrees. Thus the dashed straight line in Figure 22 at 3.73 degrees represents the NAVSEC/NAVSHIP roll stabilization goal. For purposes of this illustration, it was also assumed that VL's would also normally occur at $\sqrt{\sigma_0}$ roll motion levels.

The shaded area above the 3.72 degree stabilization line indicate regions where the launch/recovery operations were performed for roll motion conditions that exceed the roll stabilization goal. These results suggest that the actual aircraft operations can and are indeed often performed at motion levels which exceed the roll stabilization goal. In addition, there is a noticeable scarcity of cancellations or delays within the top 30 events of these sequences of VL's and STO's ordered by decreasing roll. This scarcity strongly suggests that roll does not directly contribute to delays or cancellations in the launch/recovery portion of the aircraft cycle. However, since the $\sqrt{\sigma_0}$ or statistical motion level at which aircraft events tend to occur was based on a limited sample, the conclusions about the number of aircraft events that occur at motion levels greater than the stabilization goal is somewhat tentative. It is recommended that the lull analysis procedure developed earlier in the text be applied to all of the trial data of Figures 20 through 22 in order to firmly establish the adequacy of the roll stabilization goal for aircraft operations.

In passing, it should be noted that roll stabilization systems should be functional at both high and low ship speeds because roll produces operational difficulties throughout the speed range. See Figure

24 and Table 4 for verification. The requirement for low speed roll stabilization, for example, is demonstrated by the fact that in about two-thirds of the highest ship motion Harrier landings (Figure 24, VL), the aircraft were recovered at speeds of 10 knots or less. The requirement for high speed roll stabilization on the other hand, as well as the need generally for roll stabilization, is demonstrated by a series of interrelated factors discussed in the following section.

SEA CONTROL SHIP ROLL STABILIZATION COMMENTS

STO or VL delays due to roll were rare but it was observed during the February 1973 trials that aircraft handling and movement from the deck to the flight deck was slowed down more by roll than by pitch.

As sea state increases, all aspects of the aircraft operations are affected--maintenance, handling and movement, as well as launching and recovery. It appeared to the NSRDC observers that handling, or the rate at which aircraft could be prepared in the hangar deck and then moved to the flight deck take-off position, was adversely affected before the launching and recovery operations were significantly affected. The handling operations were affected more by roll than pitch because generally roll was the greatest angular ship motion and, equally important, there is considerably less room for aircraft skids or shifts in the lateral direction (roll) than in the longitudinal direction (pitch). When the angular ship motions reached a value where the aircraft could no longer be reliably held in place by the aircraft brakes, chains were used to control its motions.

It was noted that increased handling time hindered most flight exercises. Although it is true that roll rarely caused a ready aircraft to abort a launch or retrieval. The roll motions were nevertheless of considerable concern to the operators. During both the February and April 1973 trials, a lack of available operational helicopters caused scheduled operations to be either cancelled or modified in their scope. For example, the ASW sonar barriers were reduced due to a lack of available aircraft. This lack of available aircraft for missions was most definitely associated with roll motions and the resulting degradation in the quality of the on-board maintenance. On another occasion, the extreme difficulty in the movement of the aircraft in the hangar bay due to roll forced the post-ponement of all aircraft movement until roll was reduced by a change in speed/heading. Flight operations were being maintained at the same time on a routine basis. Thus, it is clear that while flight operations are themselves less sensitive to roll than other aircraft handling or main-tenance tasks, in the final analysis it is these other aircraft operations which significantly degrade air capability of tne SCS.

CONCLUSIONS

The following statements summarize the major conclusions derived from the measured and observed data collected by the NSRDC staff during the extensive at sea deployments of the VSTOL aircraft Harrier on the Interim Sea Control Ship, the USS GUAM. (LPH-9).

1. Eighty percent of the delays or cancellations in aircraft operations were due to weather and other factors rather

than ship motions. No more than 20 percent of the operation delays or cancellations were attributable to excessive ship motions.

2. Generally, the operators attempt to perform their various tasks associated with launching and recovery of the Harriers so as to minimize the effect of ship motions. This is done by timing critical stages in the tasks to occur at lulls in the ship motions or at times when the attitude of the ship is favorable. Generally, the effect of increasing ship motions is to slow down rather than outright stop air operations.

3. Pitch is the component of ship motion that interferes significantly with the launch/recovery stages in Harrier operations. This interference is especially evident during vertical landings (VL).

4. The inability of the landing signal enlisted to accurately judge or predict the attitude of the ship's bow when the Harrier passes off the bow during the short rolling takeoffs (STO's) is a primary operational difficulty relating to pitch. In fact, the inability to predict the bow attitude is one of the most frequently noted reasons for cancelling or delaying STO's. The inability to predict bow attitude will produce delays or cancellations even at very small values of pitch, i.e., $\sqrt{Q_0}$ pitch of 0.36 degrees.

5. Pitch and the associated relative motions of the ship hull to the water surface produce water impacts on the elevators which cause delays or cancellations in aircraft operations.

6. The lowest values of pitch at which cancellations or delays occur due to ship motions (Figures 20, 23, and 24) are 3 degrees during VL's and 2.5 degrees during STO's. It is to be noted that these motions represent the double amplitudes associated with aircraft events. Refer to Figures 7 and 8 and discussion in text for definition.

7. Generally when the $\sqrt{Q_0}$ pitch motions attained levels between 1.2 and 1.5 degrees Harrier operations were delayed. When the $\sqrt{Q_0}$ pitch motions attained levels between 1.5 and 2.0 degrees operations were generally cancelled, and when $\sqrt{Q_0}$ pitch motions were greater than 2.0 degrees no Harrier operations occurred.

8. It must be noted however, that when the pitch motions were erratic so that bow attitude could not accurately be predicted Harrier cancellations occurred even at very low values of pitch, i.e., $\sqrt{Q_0}$ = 0.36 degrees. Ship motion related aircraft operation delays/cancellations therefore are not simply a function of the magnitude of the motions but rather of their basic "predictability" characteristics.

9. Roll motions primarily produce delays in the aircraft launch/retrieval operations including delays in moving the aircraft on the flight deck, the hangar deck and the elevators.

10. Roll motions appear to degrade the crew's ability to perform various aircraft maintenance functions. As roll continues at high levels for days on end, the degradation in the maintenance performance gradually causes more and more aircraft to become inoperative.

11. Launches and recoveries of the Harriers can be performed at roll and pitch motion levels that essentially prohibit the movement of the aircraft on the decks or elevator and the performance of various maintenance tasks. Thus launches and recoveries are not the most motion affected portion of the aircraft's operational cycle on the ship.

12. There is a tendency for the aircraft events (STO's) to occur at roll values corresponding to $\sqrt{2} \cdot$ RMS or $\sqrt{Q_0}$.

13. A large number of aircraft launches and retrievals were conducted at roll motion levels that appeared to exceed the Sea Control Ship roll stabilization criterion of 16 degrees roll double amplitude exceeded only once in 100 cycles.

14. The pitch plus roll criterion was not used by the aircraft operators to cancel aircraft operations irrespective of pilot statements to this effect during the (Figures 20 and 21) earlier GUAM deployments.

15. The LPH based Harrier operations were conducted under rougher ship motion conditions than those previously reported for the Harrier operations on an LPD or indeed any British or U.S.

Navy ship (Figures 20 and 21). However, some of the ship motion related cancellations or delays occurred in Sea States 3 and 4 (see Table 4).

16. Wind direction rather than the direction of the predominant sea dictates ship headings during launch/recovery operations.

17. Wind generated local waves did not produce interference for aircraft operations; instead, swells produced the ship motions that interfered with aircraft operations. Wind direction and swell direction are independent.

18. Variation in wind speed and direction over the duration of an aircraft mission and the arrival of swell in an operating area are more likely to produce difficulties with the launch/ retrieval of aircraft than the growth of the waves due to the wind.

19. The short rolling takeoffs (STO) are much more important than the vertical takeoffs for Harriers operating off Sea Control Ships. STO's allow the Harriers a much greater payload than VT's.

RECOMMENDATIONS

In conclusion, a series of recommendations is made to increase the usefulness of the Sea Control Ship in handling aircraft, including helicopters in severe weather.

1. It is recommended that the Sea Control Ship or any similar ship which employs Harriers be designed so that launches/

retrievals can be made either over the bow or the stern. This bi-directional launch/retrieval capability will significantly extend the operational capability of the ship/aircraft team (see Appendix C).

2. It is recommended that the ship be roll stabilized, especially at low speeds beyond the Sea Control Ship roll stabilization goal, if at all possible. Handling and aircraft maintenance are severely affected at lower values of roll than the Harrier launch/retrieval operations.

3. It is recommended that time and motion studies be made for extended time periods at sea to define the maintenance degradation as a function of increasing ship motions.

4. It is recommended that a long range research program be initiated to improve the operator's capability to predict pitch and roll lulls more accurately.

5. It is recommended that wider limiting wind eveloped be developed for H-3 helicopters operating off LPH's, than were employed during the GUAM's deployments as the Interim Sea Control Ship.

6. It is recommended that simultaneous measurements of ship motion and aircraft control position movements be made. These data establish which ship motion components and what levels thereof produce difficulties for the pilots which they compensate for by control movements.

7. It is recommended that a lull analysis be performed for all of the trial data of Figures 20 through 22 to establish at what statistical ship motion levels aircraft events tend to occur and at what levels cancellations occur. Until this work is done, the ship motion data of Table 4 should be used as limiting ship motions for Harrier operations off Sea Control Ships.

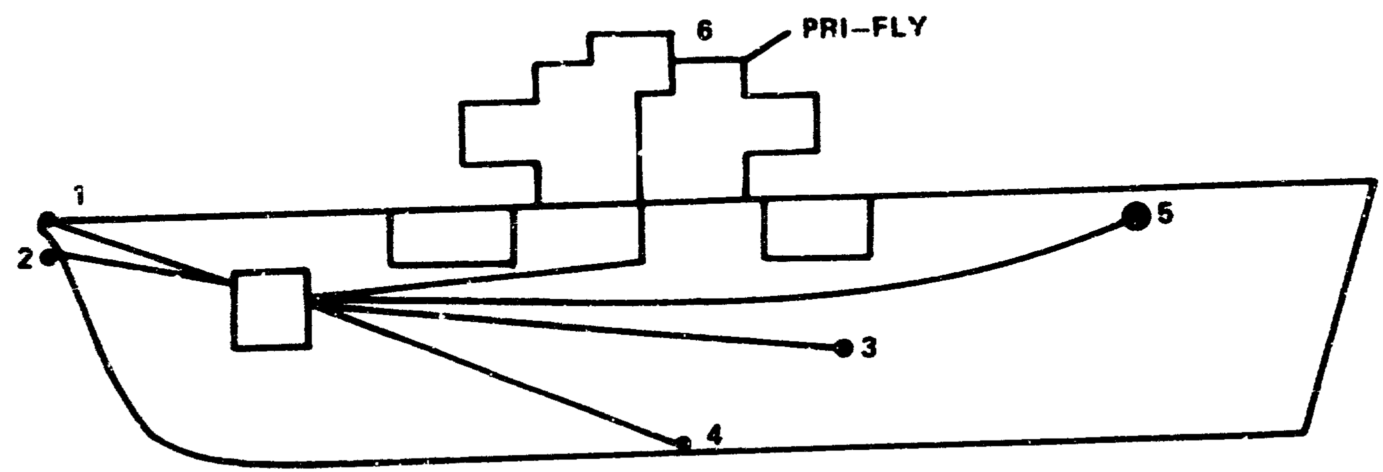
ACKNOWLEDGEMENTS

The active participation of Ms. B. Lynch of NAVAIR and Mr. F. Briggs of NAEC in defining and collecting the aircraft and ship motion data presented in this report is gratefully acknowledged. The cooperation and assistance given to the NSRDC staff members by the officers and enlisted personnel of the USS GUAM are similarly gratefully acknowledged.

The authors are particularly grateful for the patient explanations of the various operational techniques and the thoughtful responses to the many questions posed to members of the GUAM's Air Department, the officers of the OPTEVFOR ISCS team, and the pilots of the deployed Harrier squadrons.

The diligent work by Mrs. Nancy Meyers in the manual ordering of the November, December 1972 and the January 1973 ship event motion data, and the manual reading of the hundred of aircraft events associated with the Ship Motions analysis are also gratefully acknowledged.

Finally, the authors wish to thank the various staff members from NSRDC who participated in the data collection and the subsequent data reduction.



ELECTRONIC MEASUREMENTS

1 Vertical Bow Acceleration ⎤ Sea State
2 Relative Bow Motion ⎦
● 3 Ship Course - Yaw
● 4 Ship Speed
5 Pitch
5 Roll
5 Sway Acceleration ⎤ Of Aft AV-8
5 Vertical Acceleration ⎥ Touchdown
5 Surge Acceleration ⎦ Point
6 Event Time Correlation

AUDIO–VISUAL DATE FROM PRI–FLY

NSRDC

6 Run Number
6 Event Number
6 Event Type
6 Event Location On Deck
6 Clock Time
● 6 Windover Deck Speed And Direction
6 Ship Course
● 6 LSO / Pilot Comments On Unusual A/C OPS
● 6 NSRDC Reps Comments
● 6 Details On OP Procedures For Ship /A/C System Affected By Sea And Weather

● NAEC

6 Run Number
6 Event Number
6 Event Type
6 Clock Time
6 A/C Side No.
6 A/C WT
6 A/C Load Config.
6 Air Temperature
6 Air Density
6 LSO / Pilot Comment On Unusual A/C OPS
6 NAEC Reps Comments

Figure 1 - NSRDC's GUAM Instrumentation Arrangement

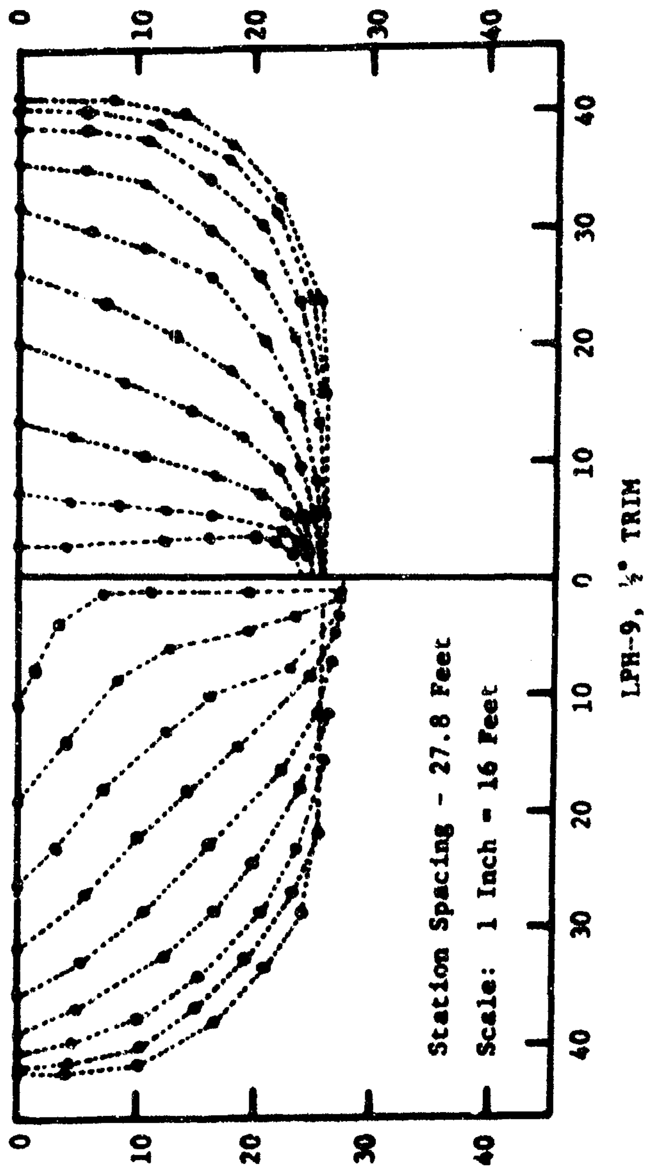
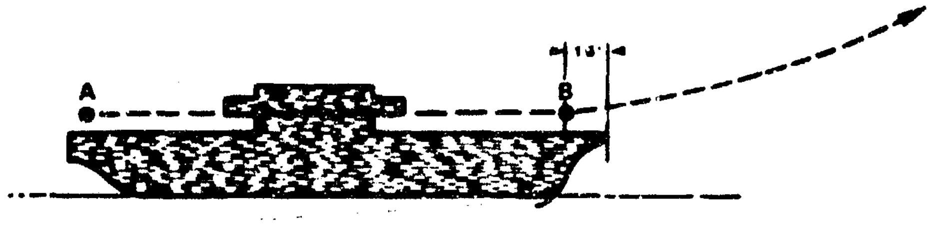


Figure 2 - Computer Fit of LPH-9 - USS GUAM Hull Lines with ½ Degree Trim Bow Up

SHORT TAKEOFF (STO - ROLLING TAKEOFF)



VERTICAL TAKEOFF (VT)

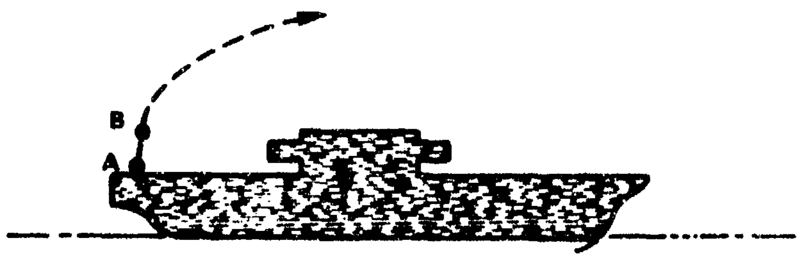


Figure 3 - Illustration of Two Types of AV8 Takeoffs

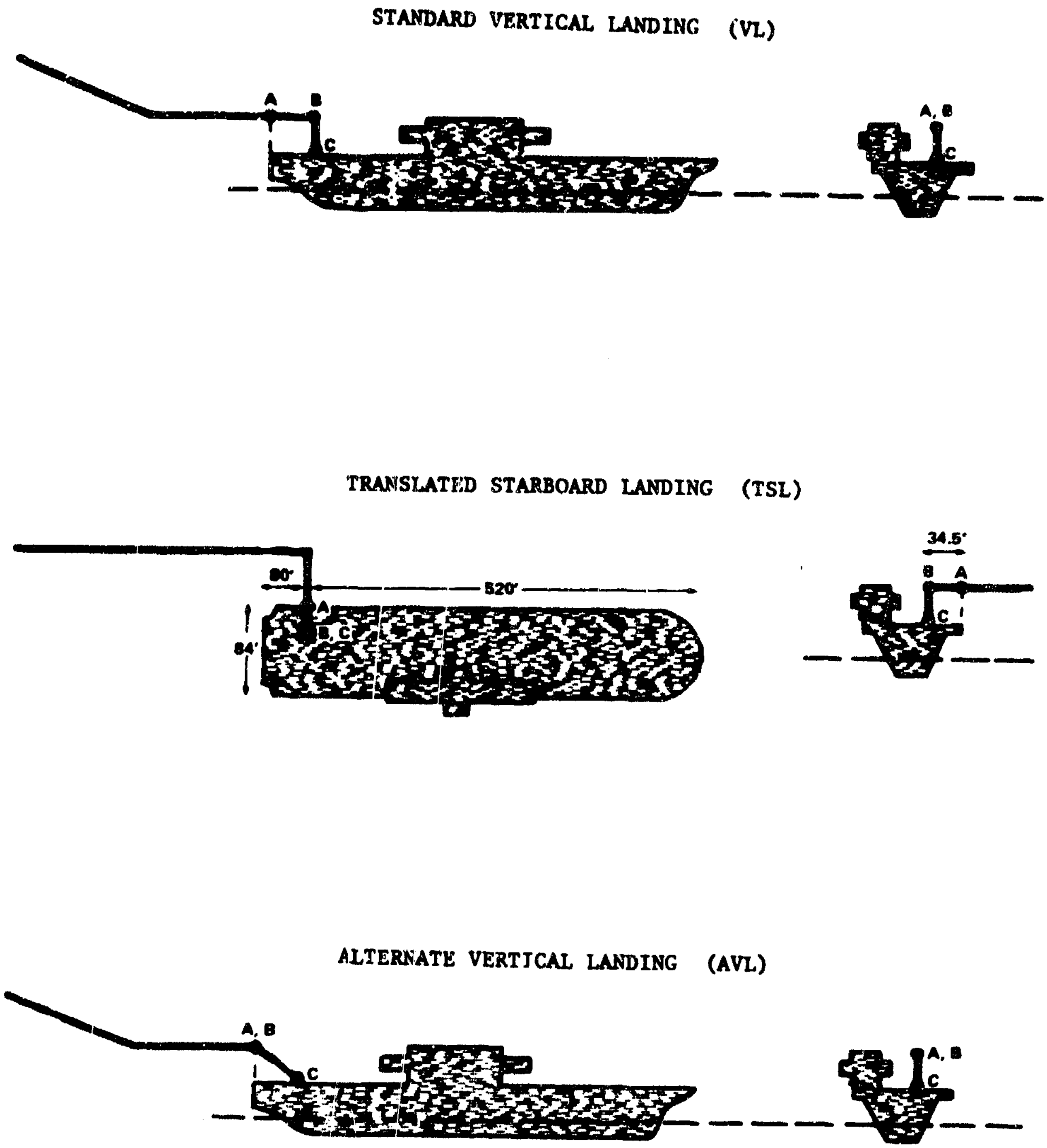


Figure 4 - Illustration of Three Types of AV8 Vertical Landings

Figure 5 - Photograph Showing Cross-Deck Landing of AV8 on GUAM Deck

AIRCRAFT EVENT SHIP MOTION DATA ORDERED BY DOUBLE AMPLITUDE VALUES

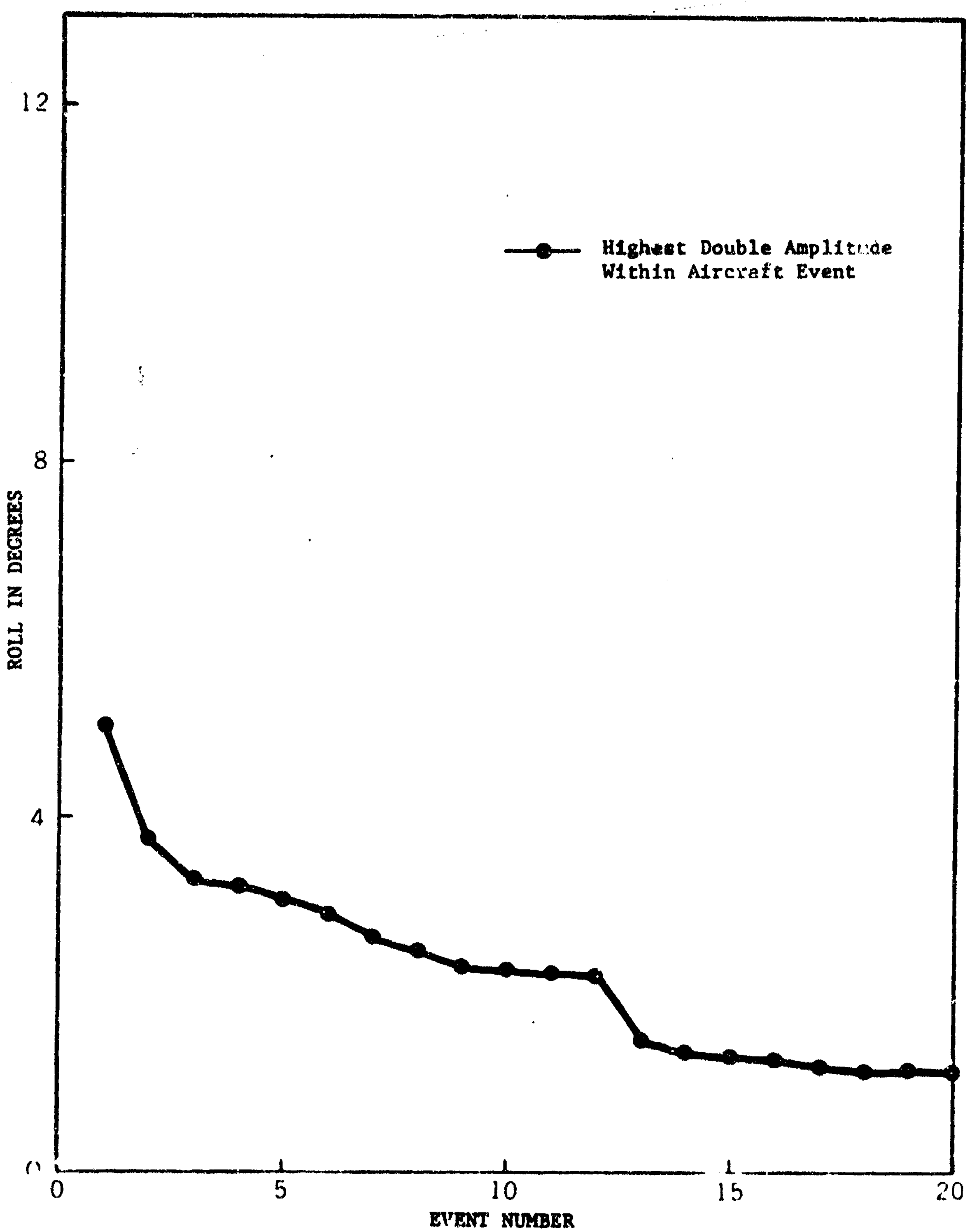


Figure 6 - Typical Ordering by Double Amplitude Ship Motion Experienced During Aircraft Events

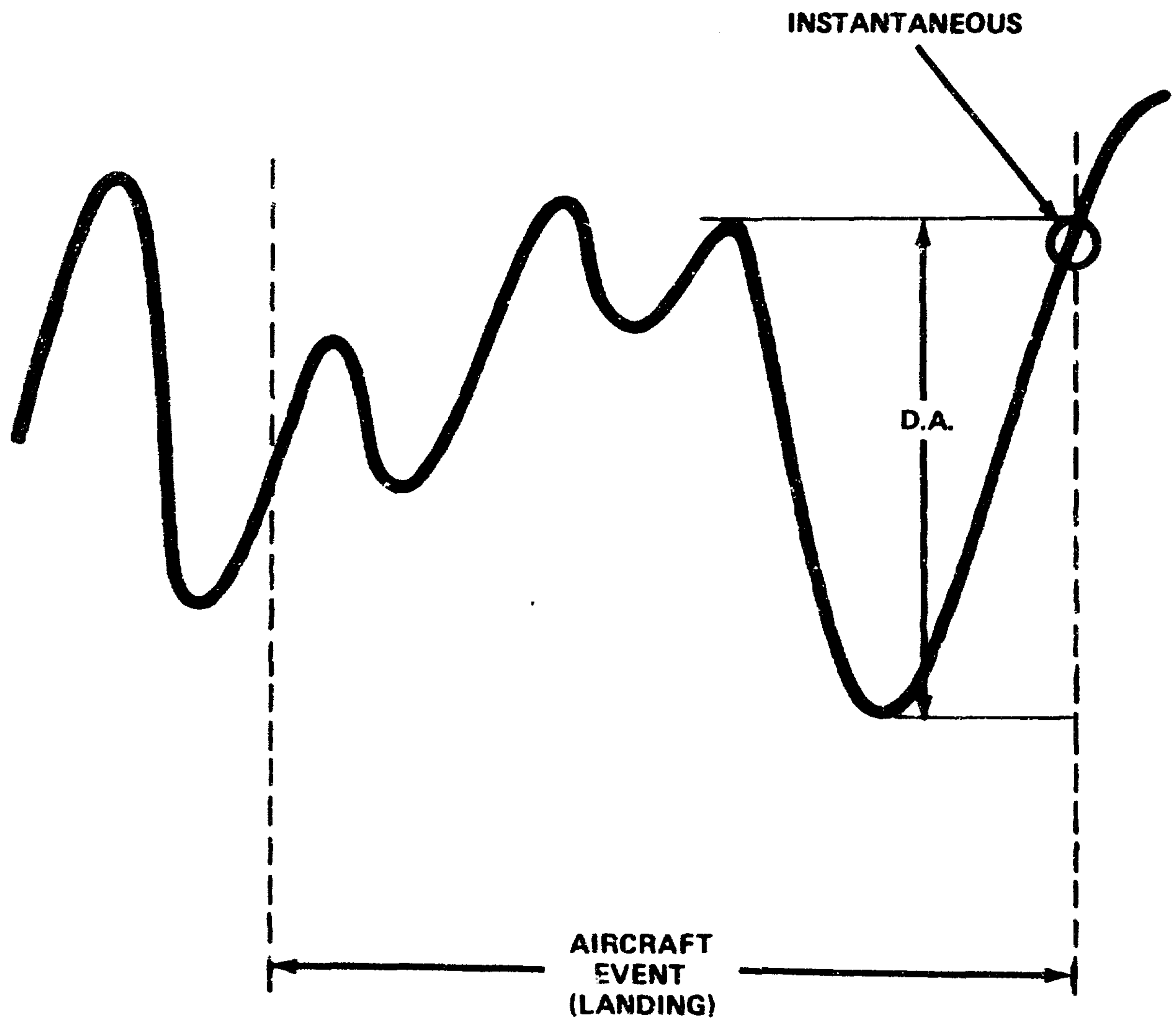
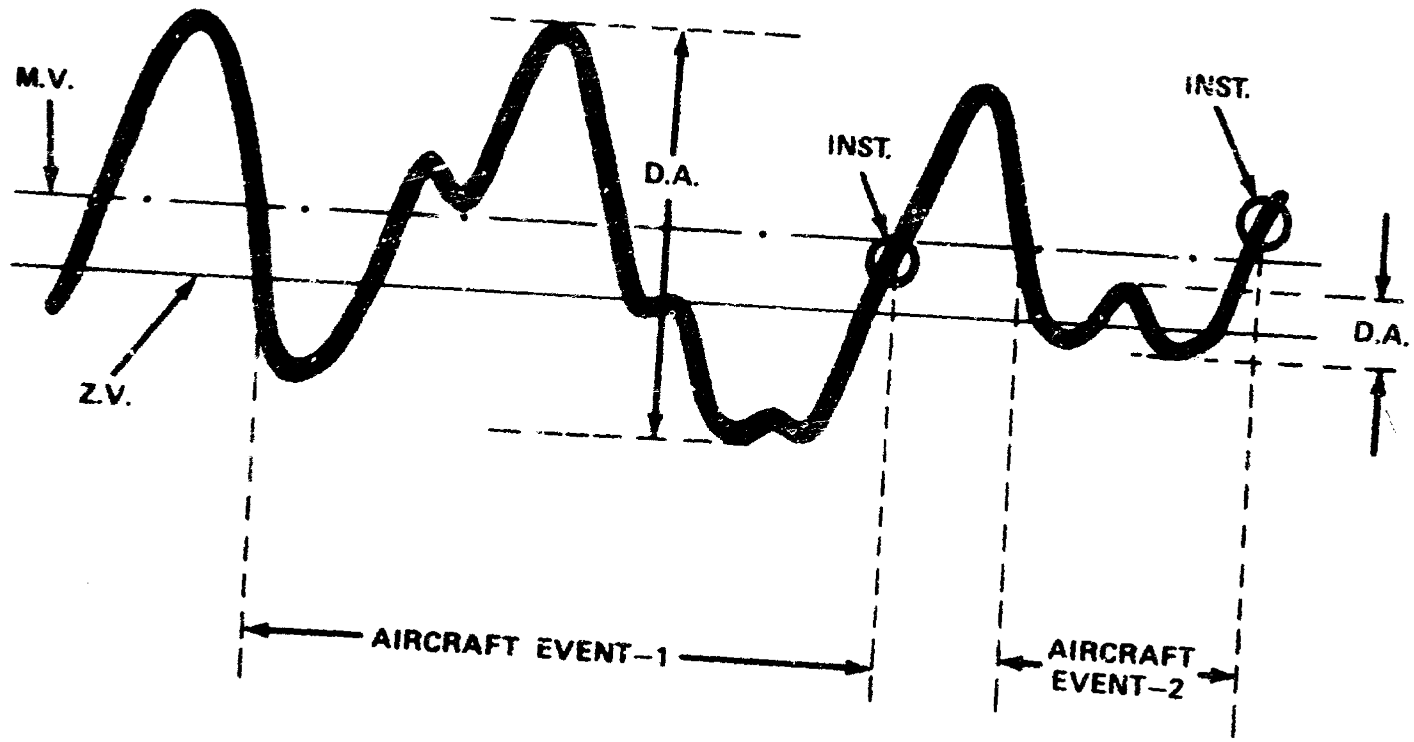


Figure 7 - Double Amplitude and Instantaneous Ship Motion Definition



D.A. = DOUBLE AMPLITUDE OF SHIP RESPONSE

INST. = INSTANTANEOUS VALUE OF SHIP RESPONSE

—— - —— = M.V., MEAN VALUE ABOUT WHICH SHIP MOTIONS OSCILLATE

———— = Z.V., ZERO VALUE REFERENCED TO SHIPS BUBBLES IN PORT

Figure 8 - Elaboration on Ship Motion Measured Definition

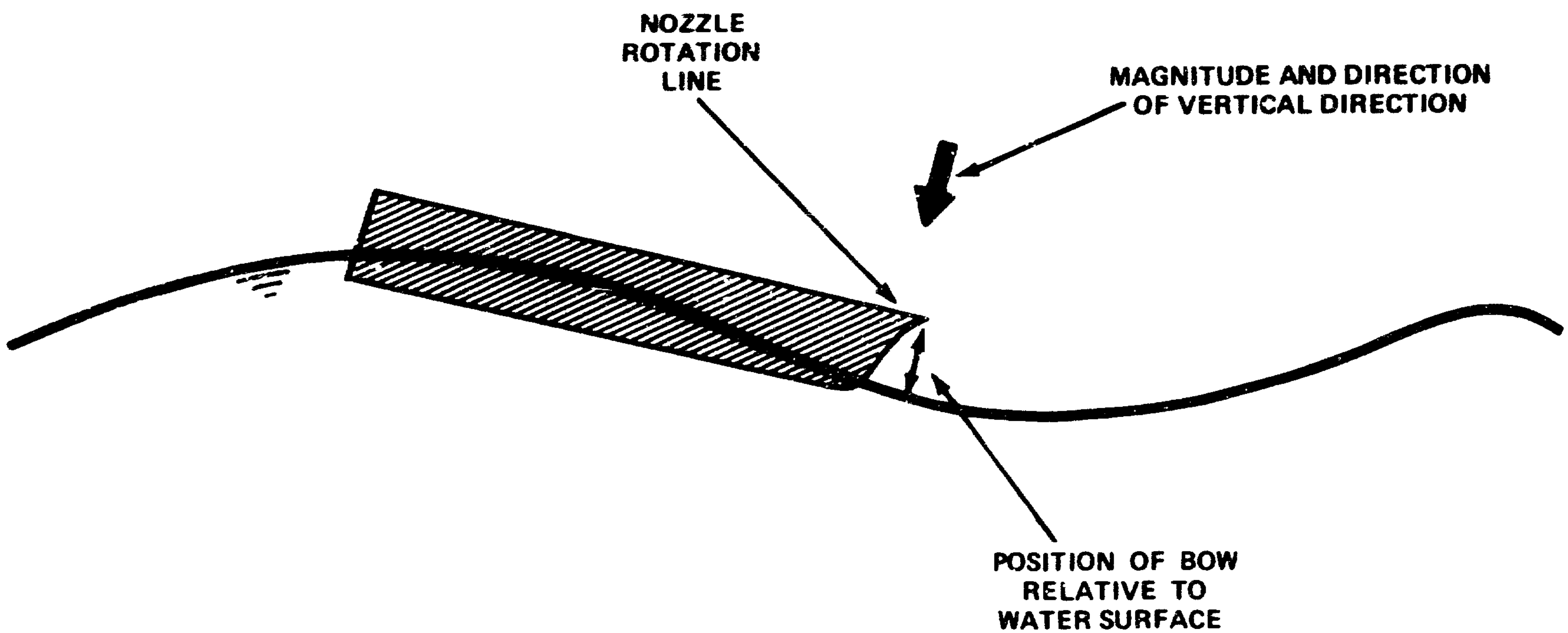


Figure 9 - Illustration of a STO Bow Down Launch

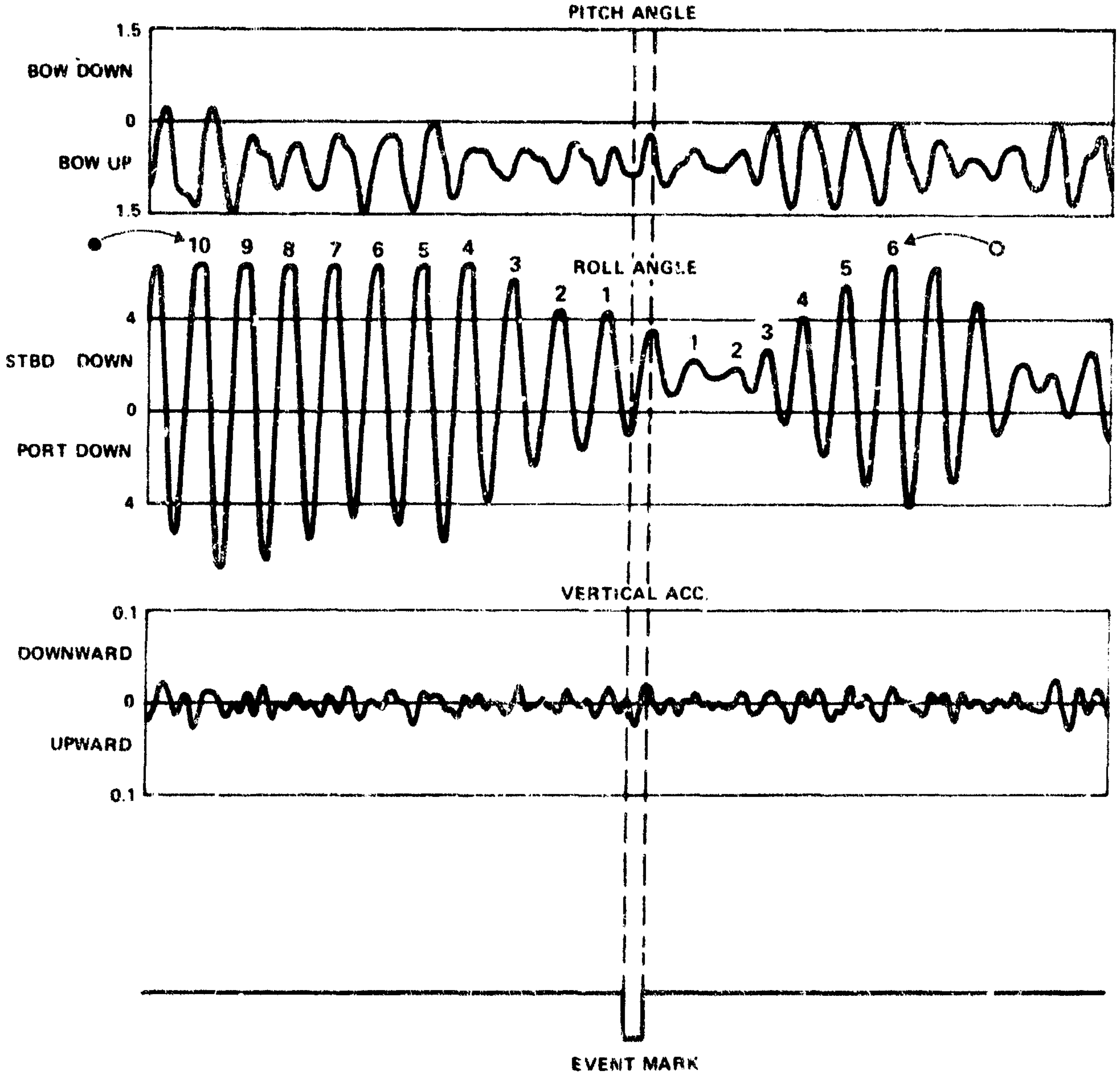


Figure 10 - Typical Aircraft Event During Lull of Ship Motion

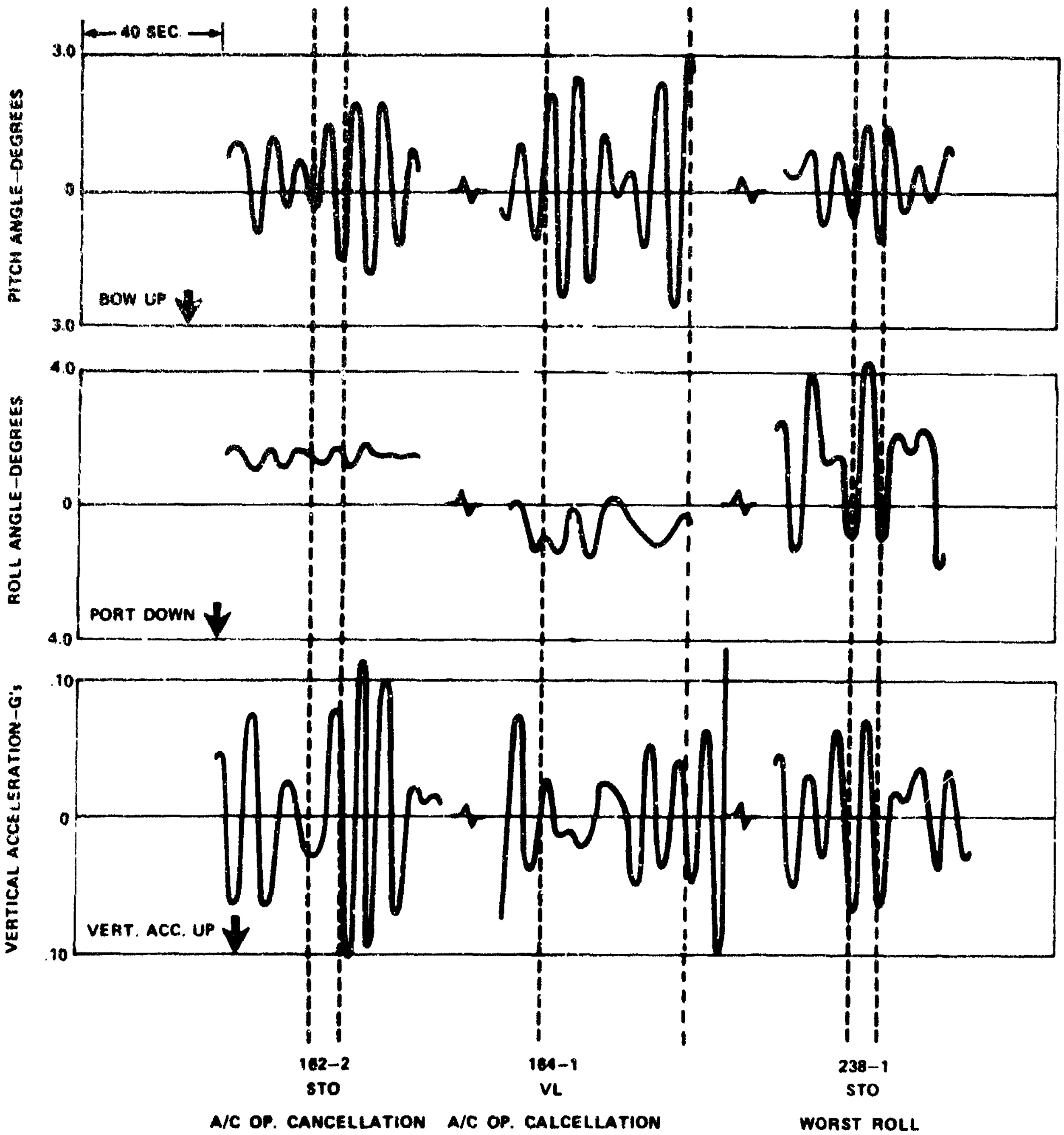


Figure 11 - Time History of Last STO and VL Before Cancellation of Aircraft Operations Due to Ship Motions, and STO with Worst Roll (Nov, Dec, Jan)

AIRCRAFT EVENT SHIP MOTION DATA ORDERED BY DOUBLE AMPLITUDE VALUES

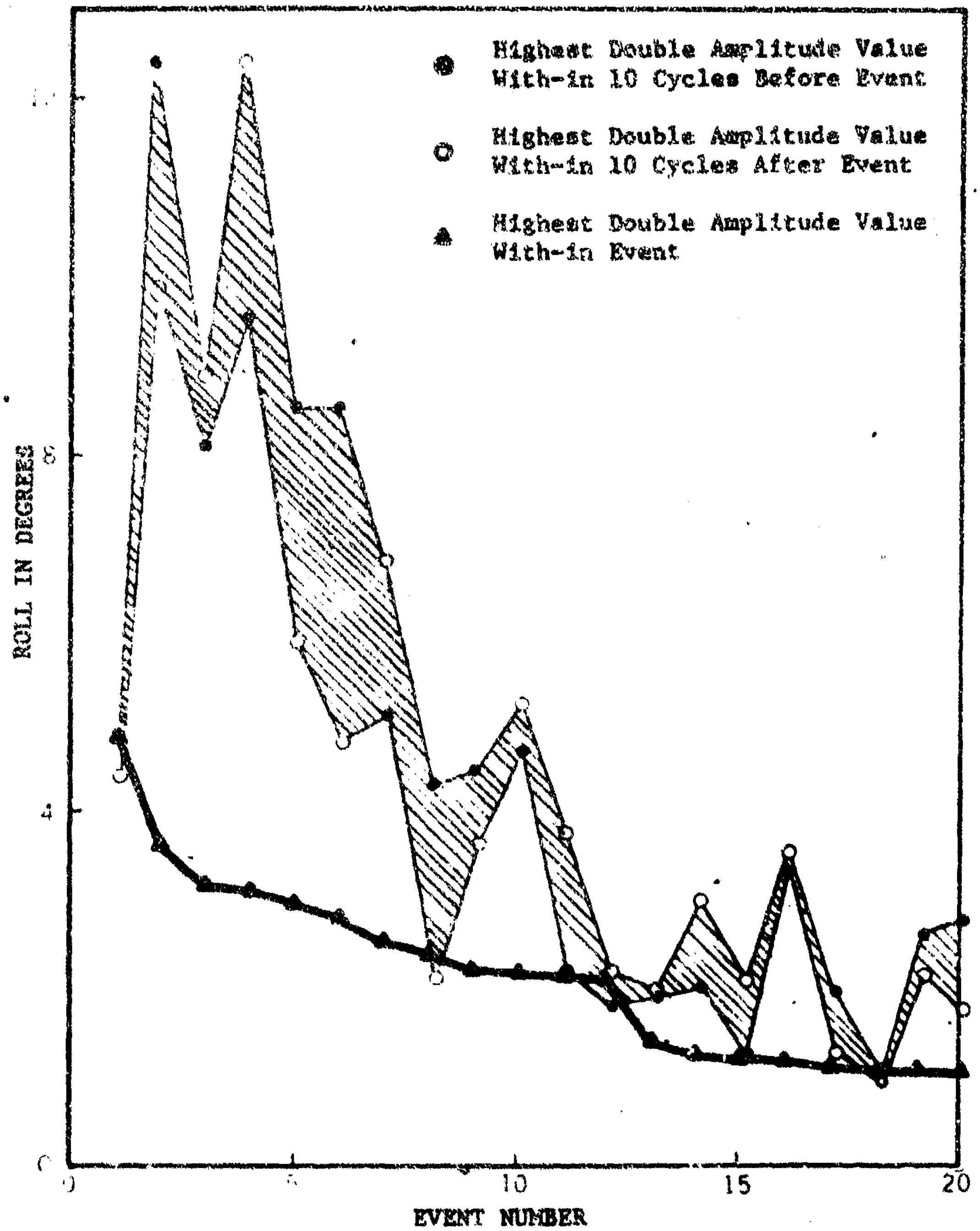


Figure 12 - Short Takeoffs (STO's) Related to Ship Motion Lulls

AIRCRAFT EVENT SHIP MOTION DATA ORDERED BY DOUBLE AMPLITUDE VALUES

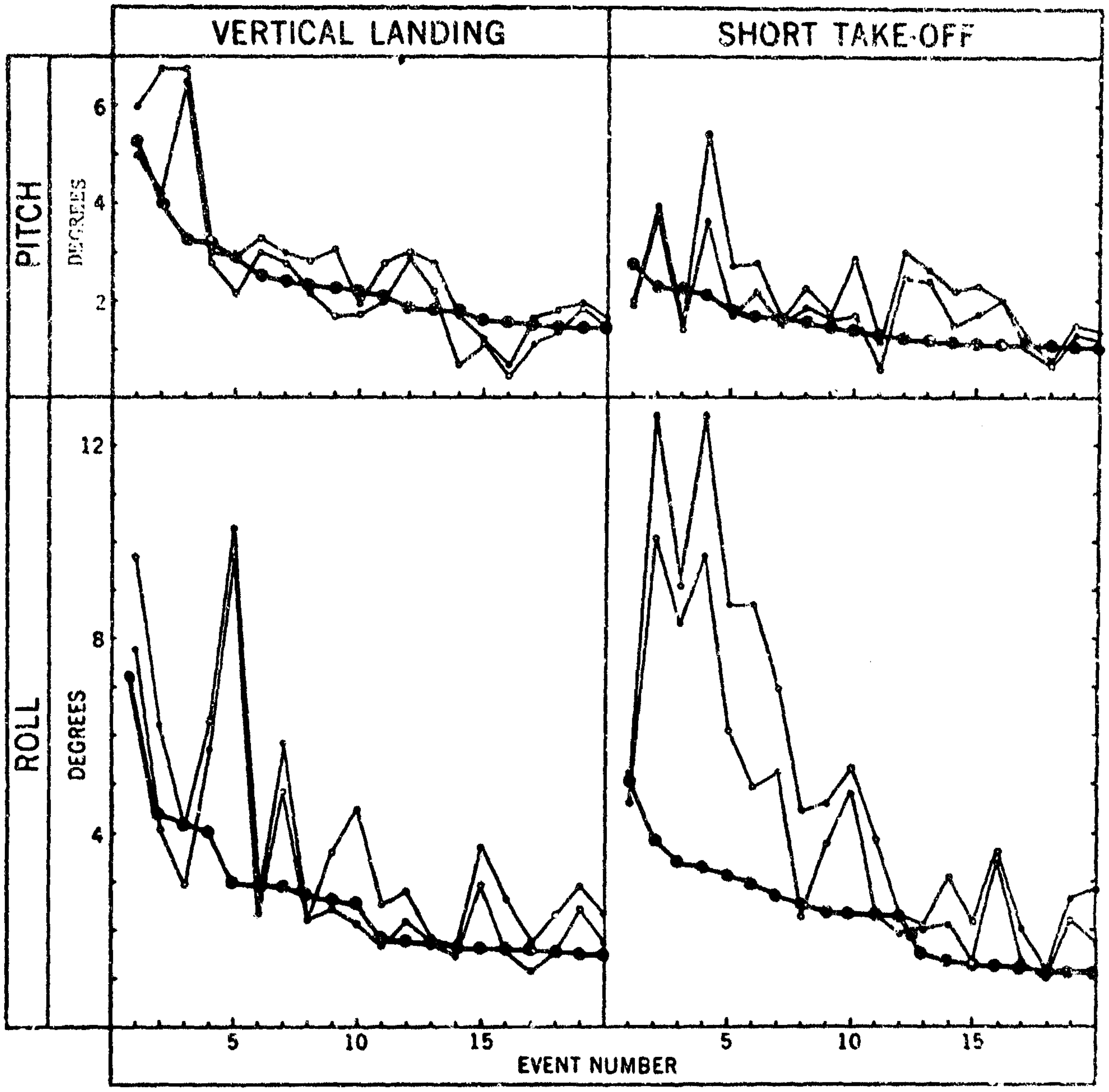


Figure 13 - Typical Aircraft Operations Related to Ship Motion Lulls

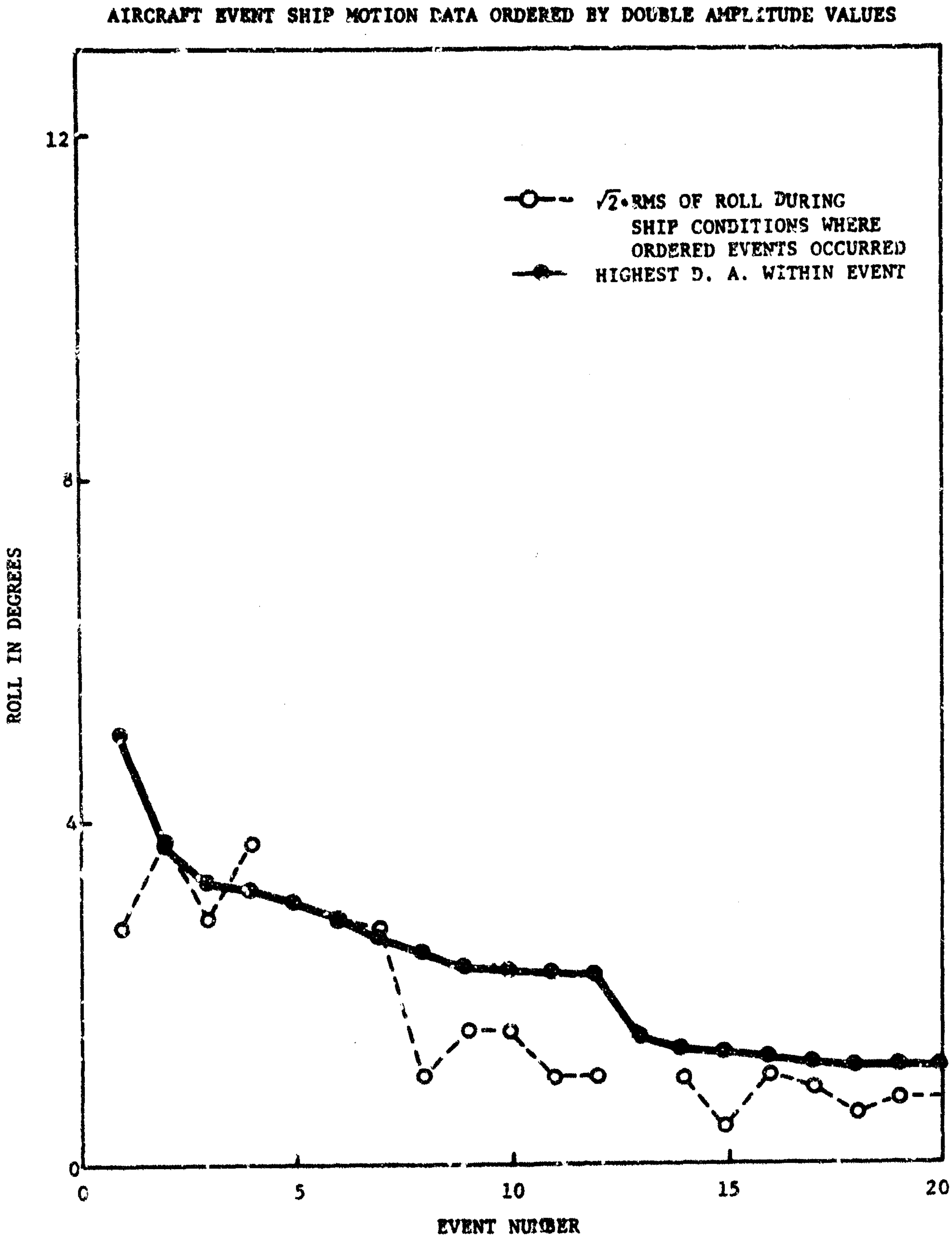


Figure 14 - Short Takeoffs Related to a Standard Measure of Ship Motion

AIRCRAFT EVENT SHIP MOTION DATA ORDERED BY DOUBLE AMPLITUDE VALUES

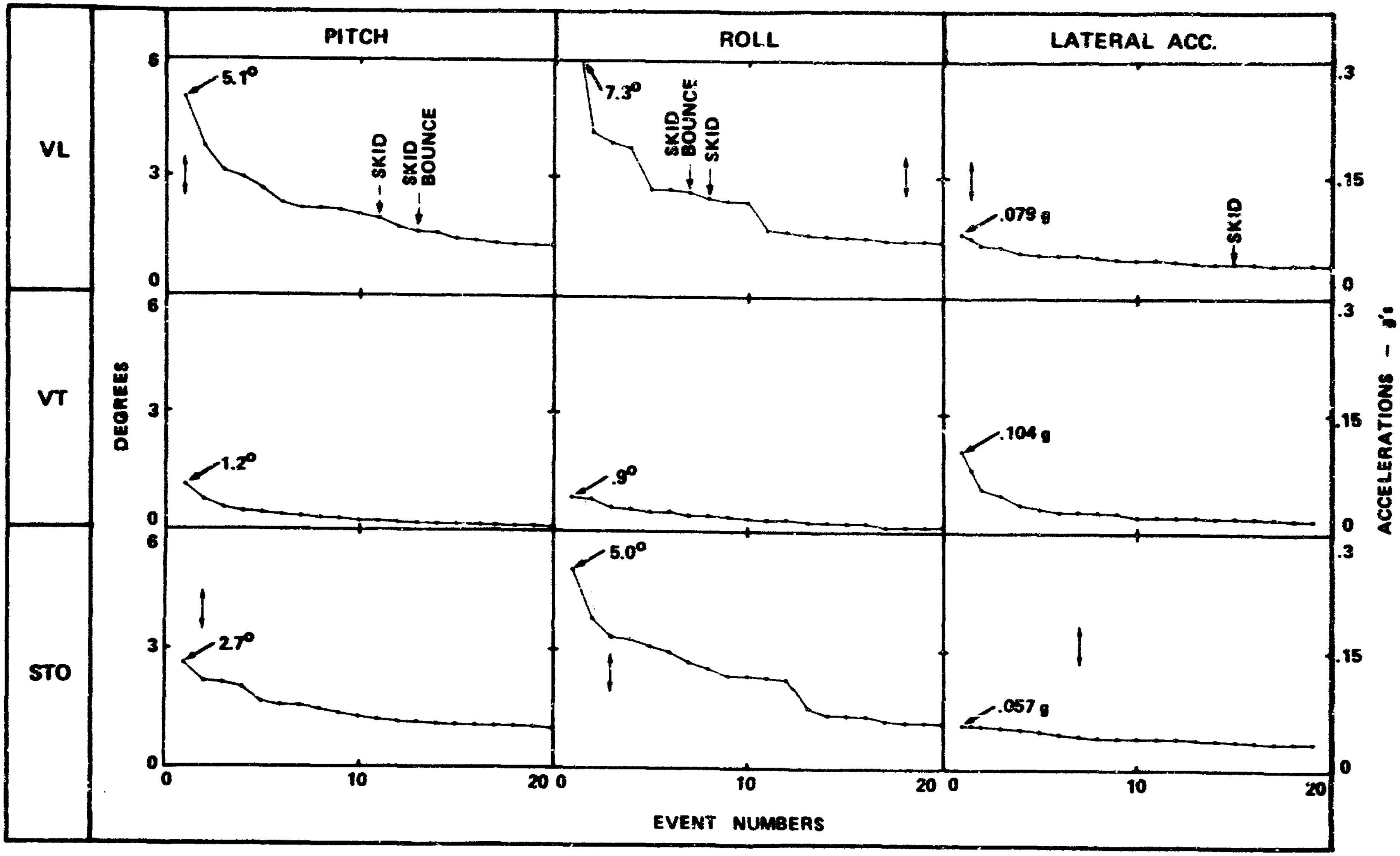


Figure 15 - Ship Motion Summary for Three Types of Aircraft Events (Nov, Dec, Jan)

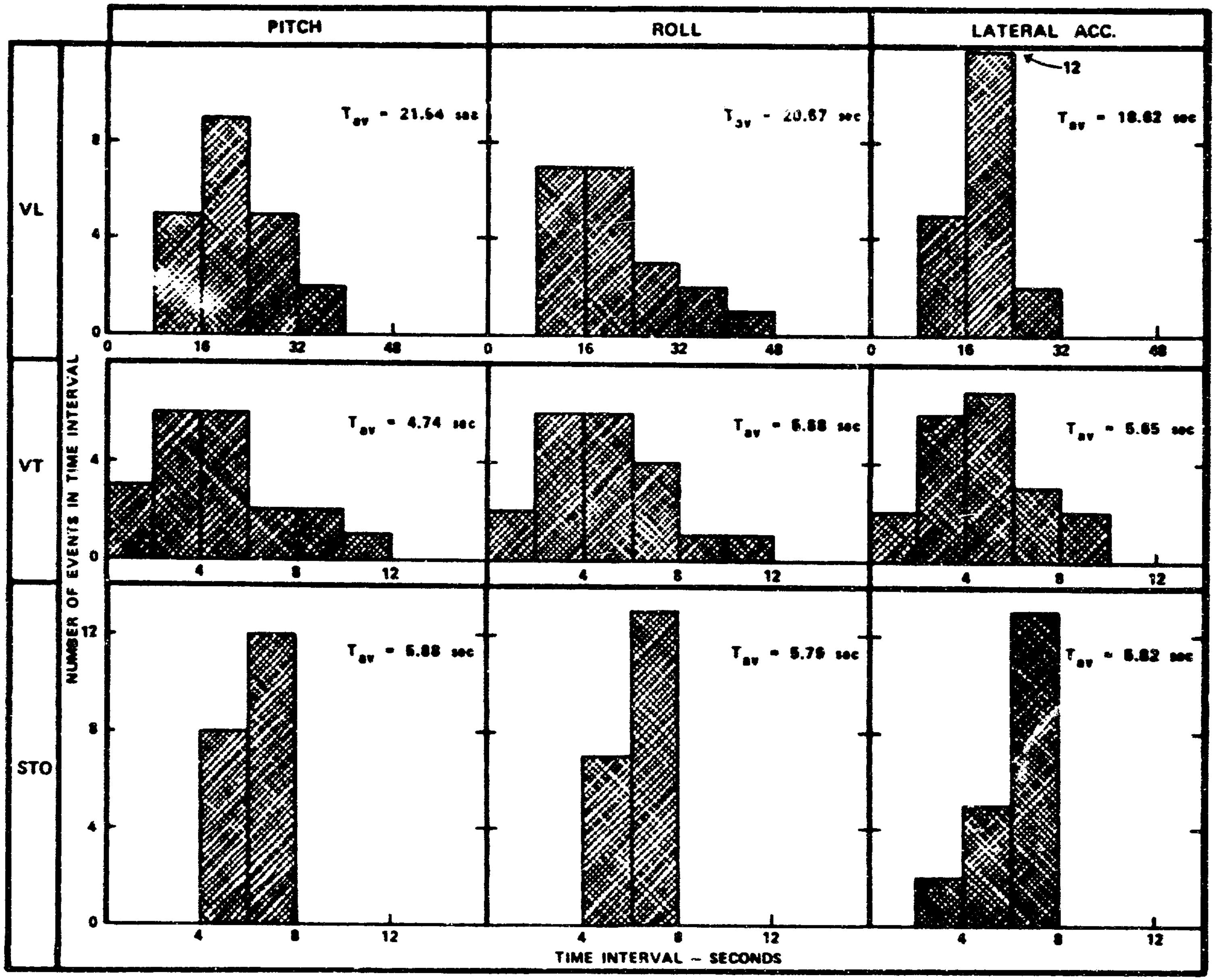


Figure 16 - Event Time Length Summary for Three Types of Aircraft Events (Nov, Dec, Jan)

AIRCRAFT EVENT SHIP MOTION DATA ORDERED BY DOUBLE AMPLITUDE VALUES

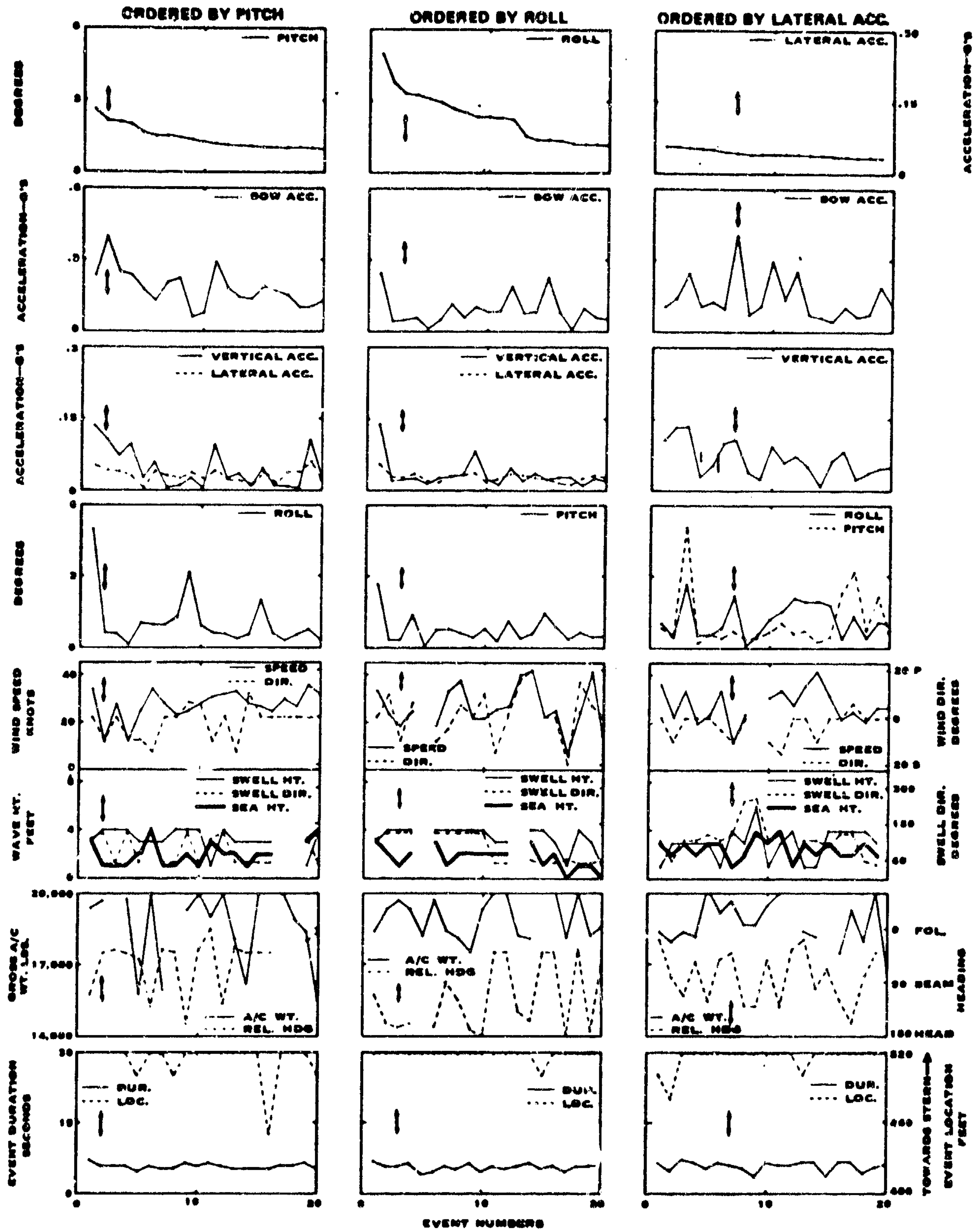


Figure 17 - Short Takeoff Ship Motion/Aircraft Correlations Ordered According to Double Amplitude Pitch, Roll, and Lateral Acceleration (Nov, Dec, Jan)

AIRCRAFT EVENT SHIP MOTION DATA ORDERED BY DOUBLE AMPLITUDE VALUES

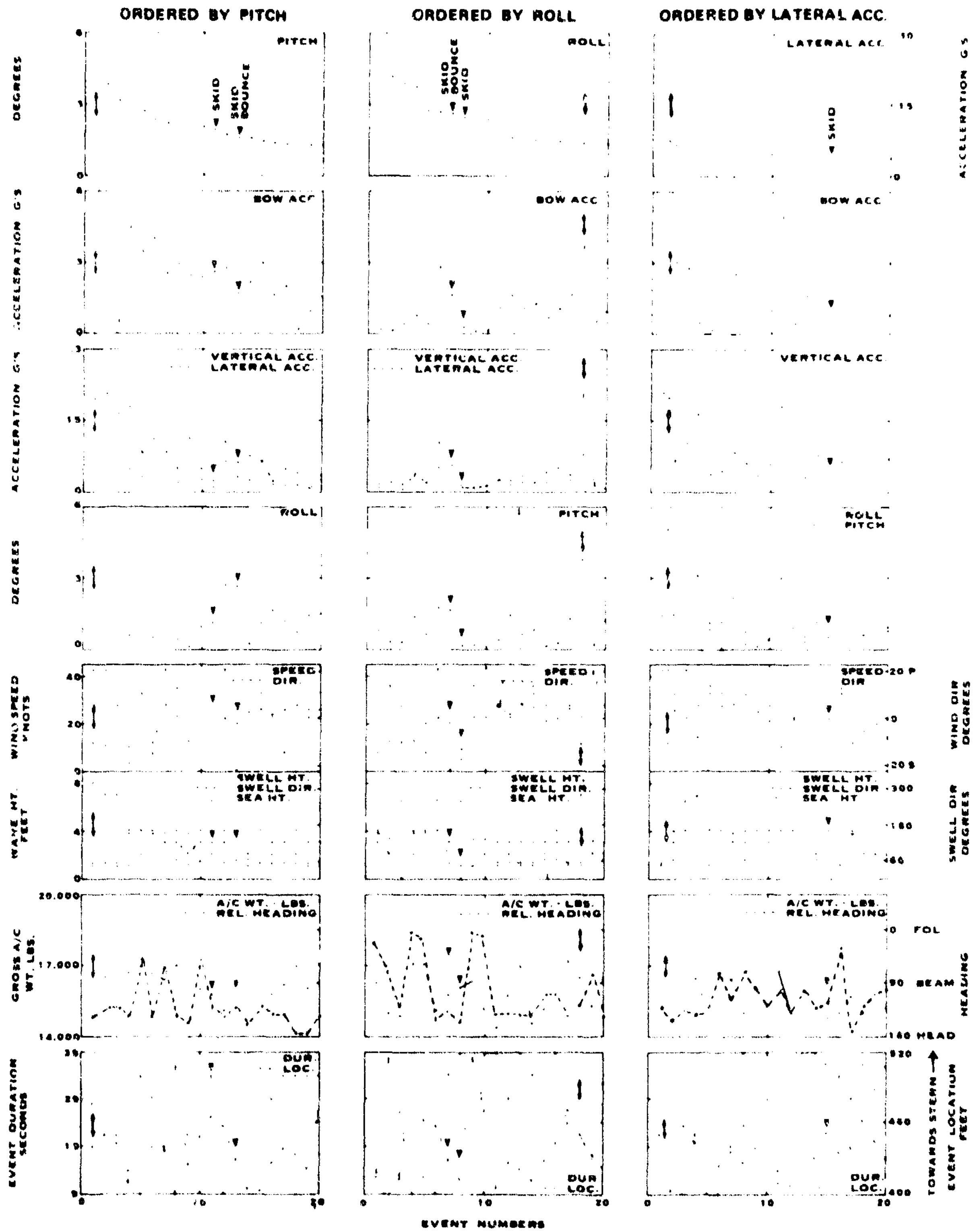


Figure 18 - Vertical Landing Ship Motion/Aircraft Correlations Ordered According to Double Amplitude Pitch, Roll, and Lateral Acceleration (Nov, Dec, Jan)

AIRCRAFT EVENT SHIP MOTION DATA ORDERED BY DOUBLE AMPLITUDE VALUES

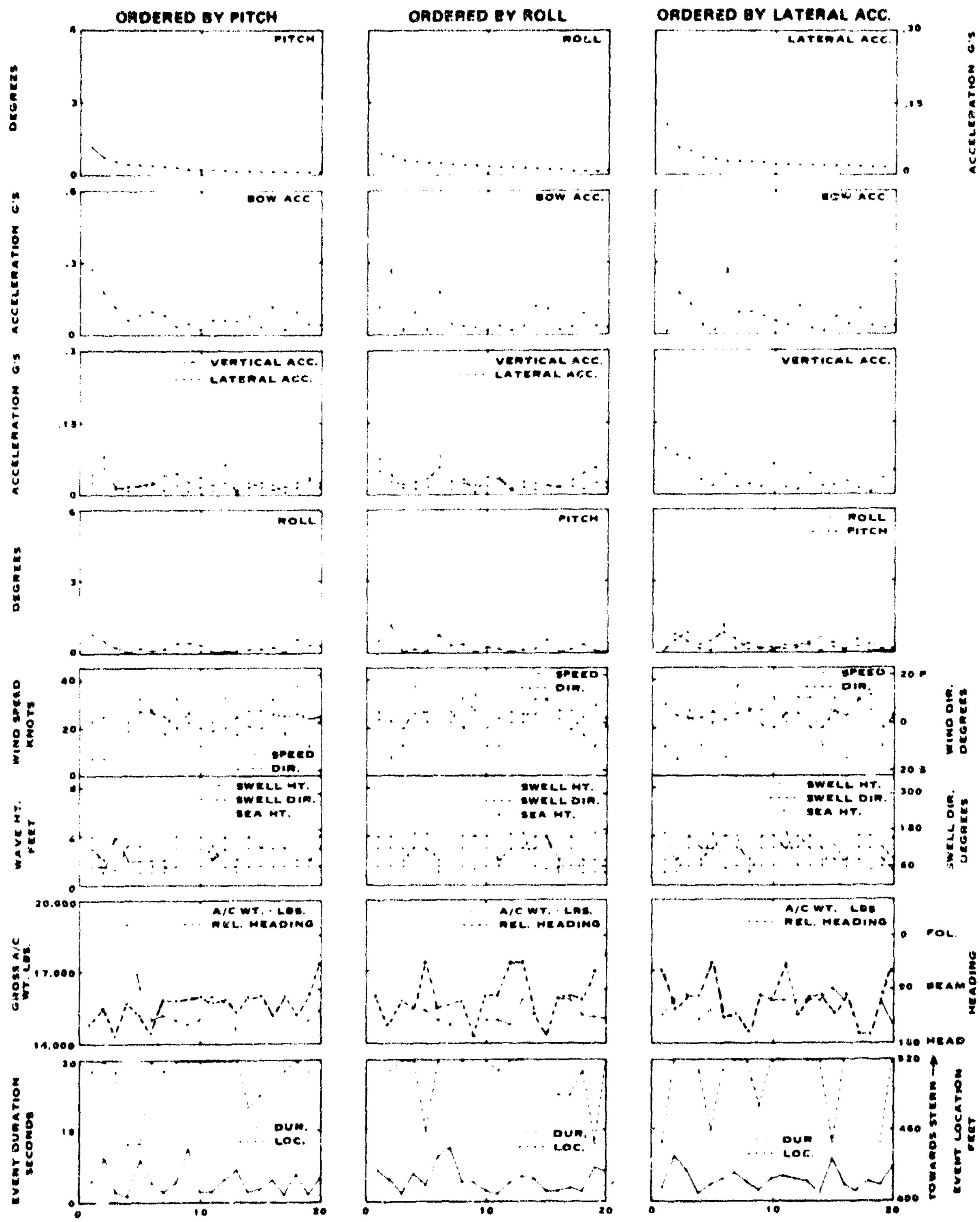


Figure 19 - Vertical Takeoff Ship Motion/Aircraft Correlations Ordered According to Double Amplitude Pitch, Roll, and Lateral Acceleration (Nov, Dec, Jan)

Numbered Arrows Denote Cancellations
and Delays as Given in Table 4

AIRCRAFT EVENT SHIP MOTION DATA ORDERED BY DOUBLE AMPLITUDE VALUES

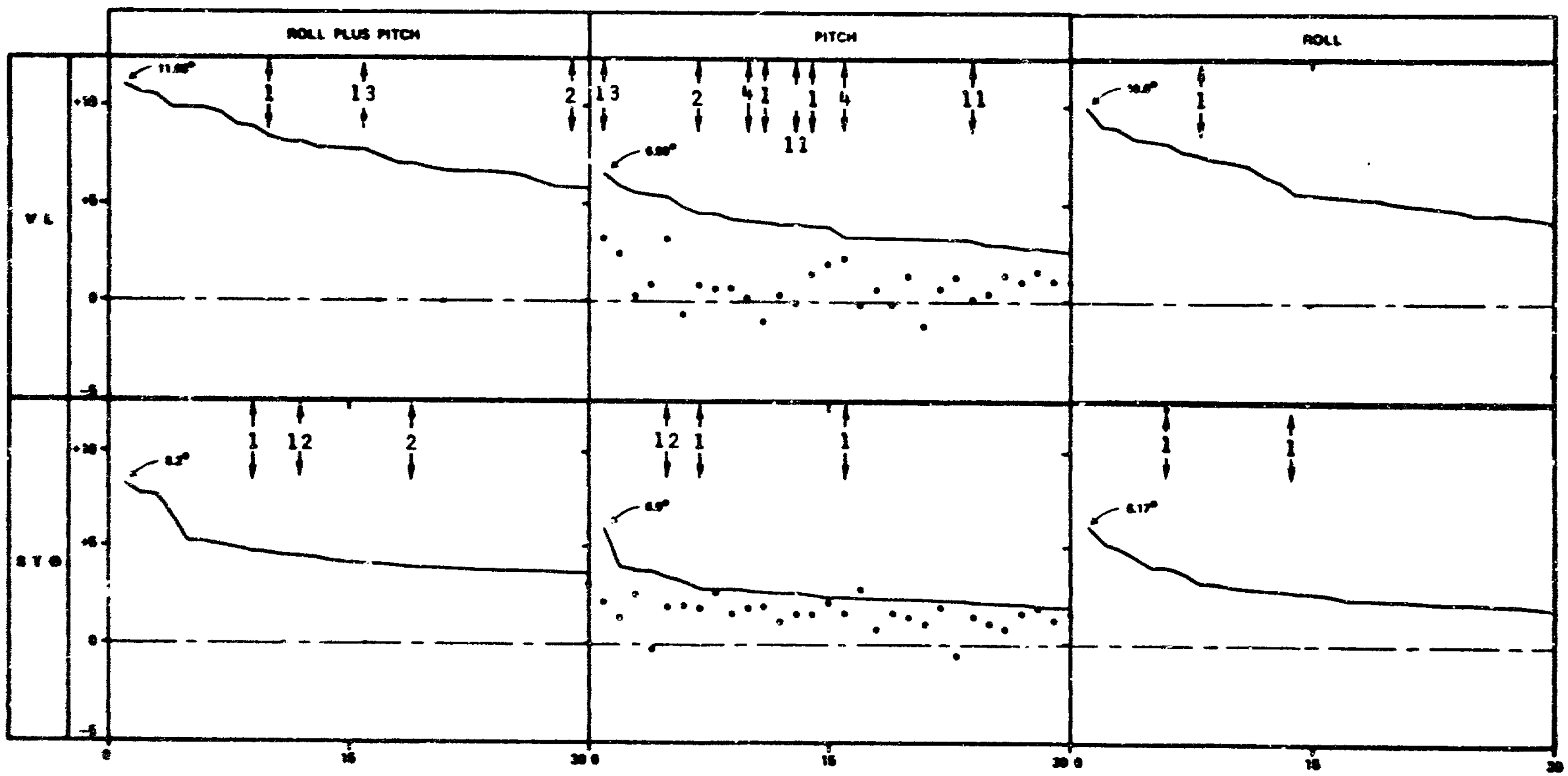


Figure 20 - Summary of Ship Motions (Double Amplitude) During Aircraft Events Ordered by Roll and Pitch, Pitch, and Roll - ALL TRIALS

Numbered Arrows Denote Cancellations
and Delays as Given in Table 4

AIRCRAFT EVENT SHIP MOTION DATA ORDERED BY INSTANTEOUS VALUES

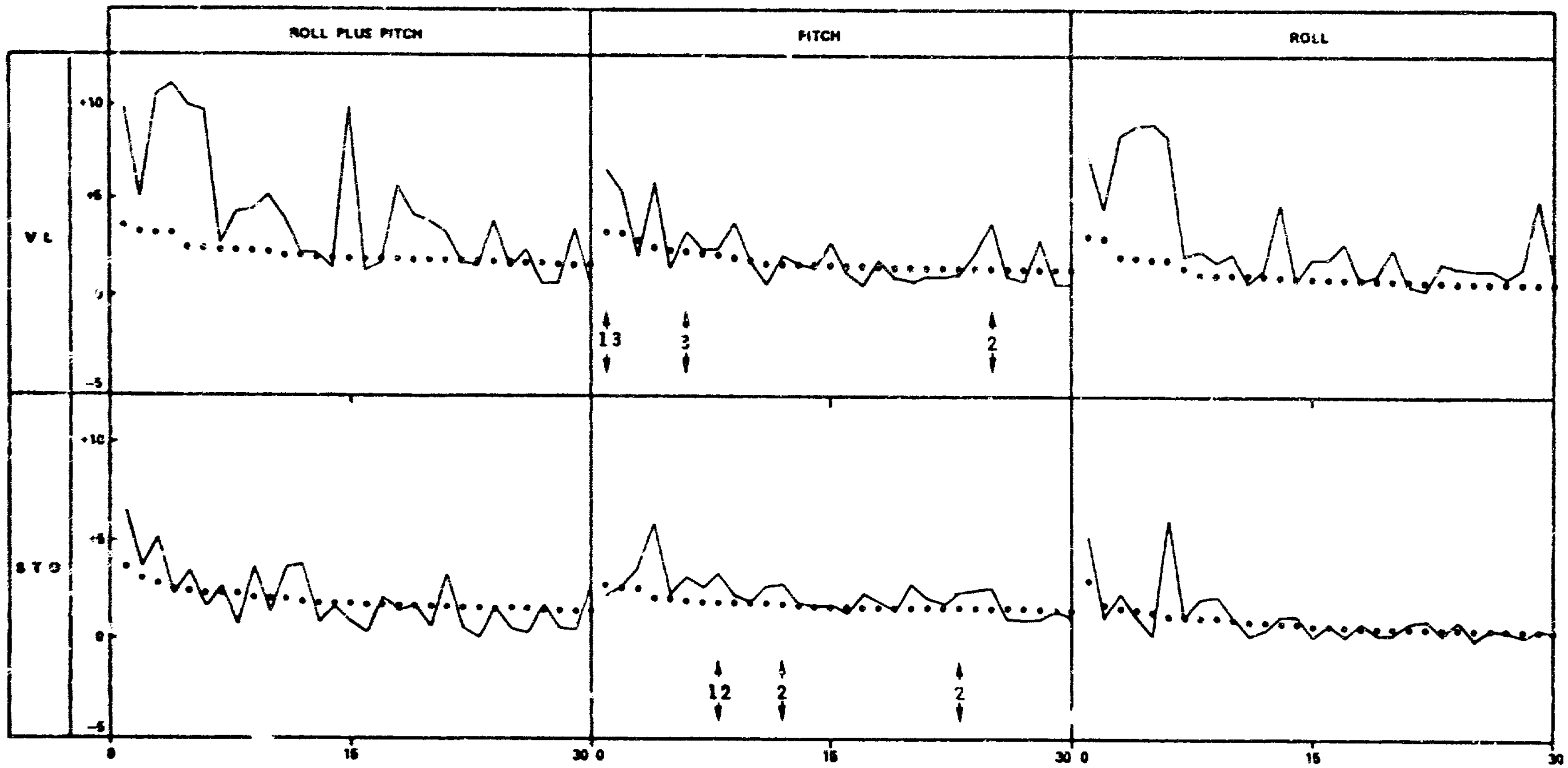


Figure 21 - Summary of Ship Motions (Instantaneous) During Aircraft Zvents - ALL TRIALS

Numbered Arrows Denote Cancellations
and Delays as Given in Table 4

AIRCRAFT EVENT SHIP MOTION DATA ORDERED BY DOUBLE AMPLITUDE VALUES

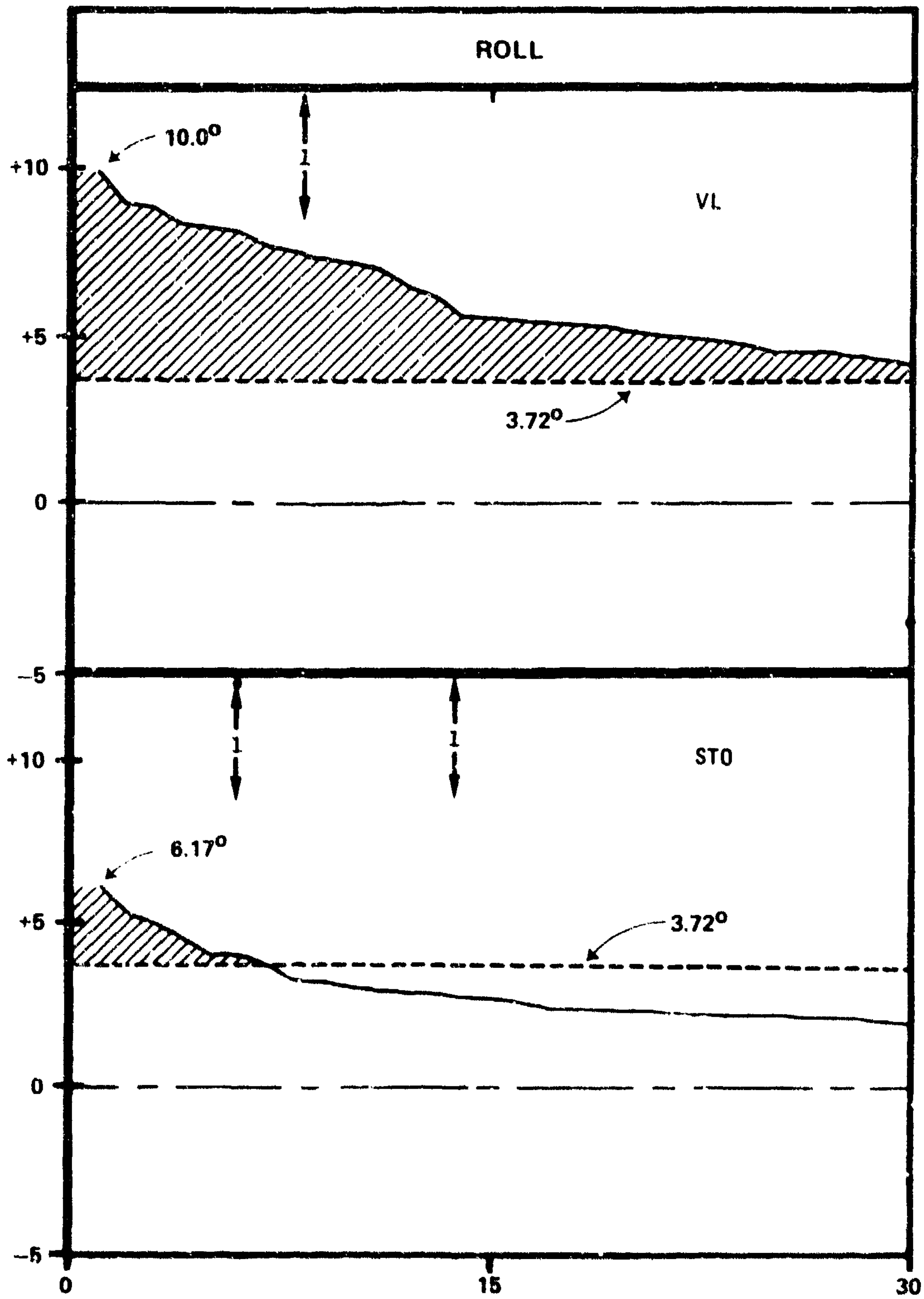


Figure 22 - Summary of Ship Motions (Double Amplitude) During Aircraft Events Ordered by Roll - ALL TRIALS

Numbered Arrows Denote Cancellations
and Delays as Given in Table 4

AIRCRAFT EVENT SHIP MOTION DATA ORDERED BY DOUBLE AMPLITUDE VALUES

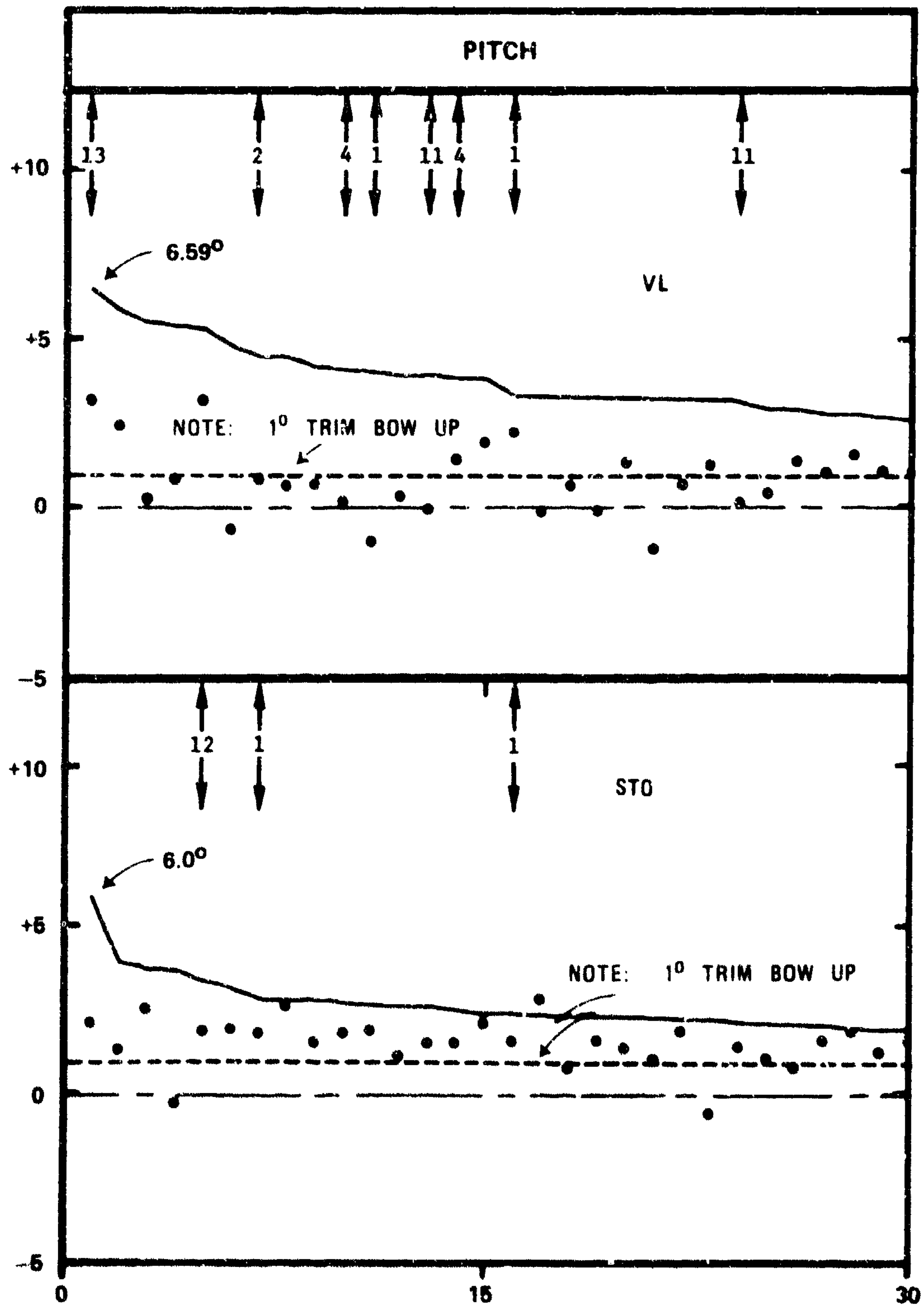


Figure 23 - Summary of Ship Motions (Double Amplitude) During Aircraft Events Ordered by Pitch - ALL TRIALS

Numbered Arrows Denote Cancellations
and Delays as Given in Table 4

ALL DATA

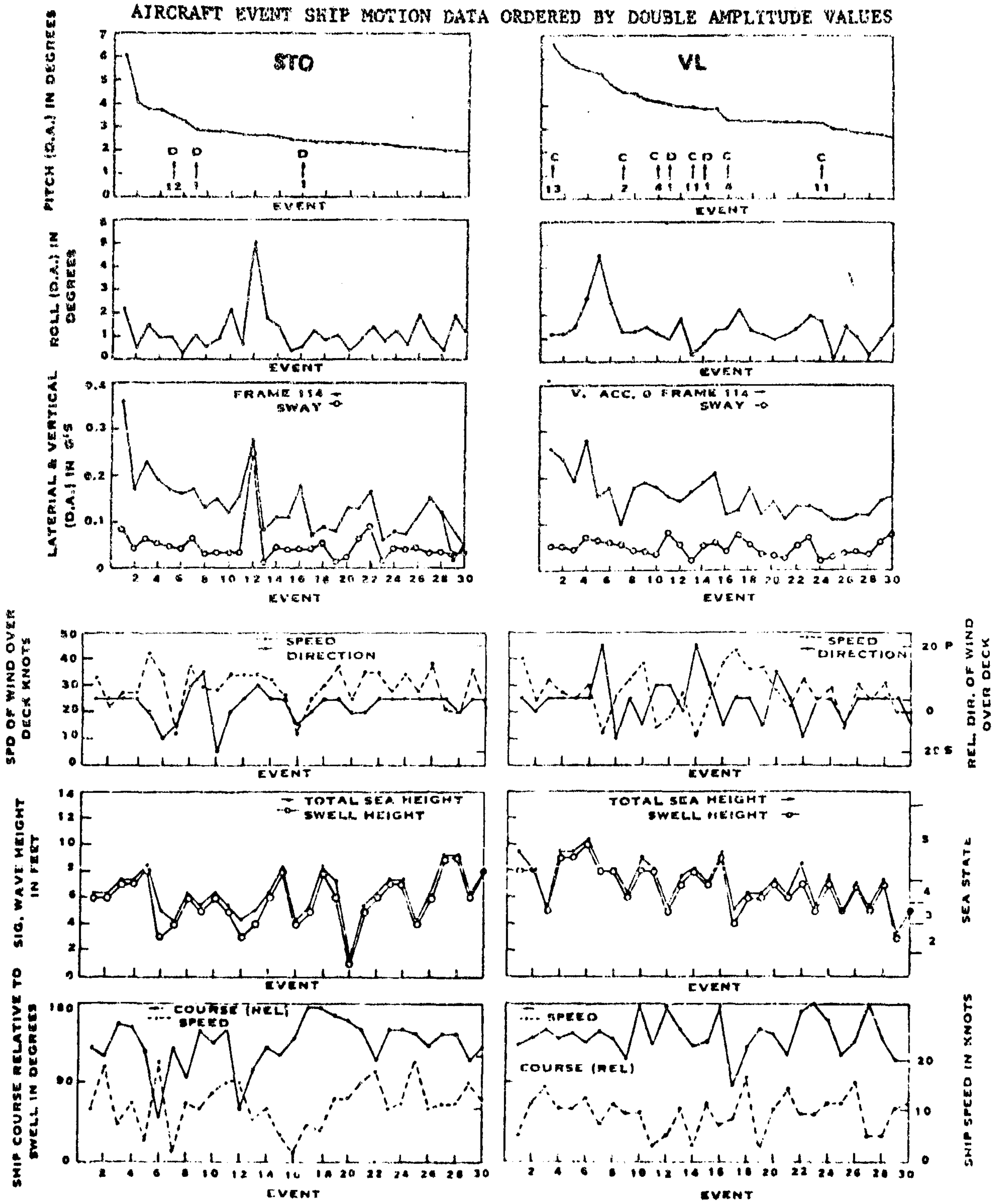


Figure 24 - Short Takeoff and Vertical Landing Ship Motion/Aircraft Correlations Ordered According to Pitch Double Amplitudes - ALL TRIALS

TABLE 1 - STATISTICAL CONSTANTS FOR SINGLE AND DOUBLE AMPLITUDE SHIP MOTIONS AND WAVE HEIGHTS

Single Amplitude Statistics

Root mean square amplitude, RMS	= 1.00 σ
Average amplitude	= 1.25 σ
Average of highest 1/3 amplitudes, significant	= 2.00 σ
Highest expected amplitude in 10 successive amplitudes	= 2.15 σ
Average of highest 1/10 amplitudes	= 2.55 σ
Highest expected amplitude in 30 successive amplitudes	= 2.61 σ
Highest expected amplitude in 50 successive amplitudes	= 2.80 σ
Highest expected amplitude in 100 successive amplitudes	= 3.03 σ
Highest expected amplitude in 200 successive amplitudes	= 3.25 σ
Highest expected amplitude in 1000 successive amplitudes	= 3.72 σ

Double Amplitude Statistics

Root que zero, $\sqrt{Q_0} = \sqrt{E} = \sqrt{2\sigma^2} = \sqrt{2}$ RMS	1.00 RQO
Average double amplitude	1.77 RQO
Average of highest 1/3 double amplitudes, significant	2.83 RQO
Highest expected double amplitude in 10 cycles	3.04 RQO
Average of highest 1/10 double amplitudes	3.61 RQO
Highest expected double amplitude in 30 cycles	3.69 RQO
Highest expected double amplitude in 50 cycles	3.96 RQO
Highest expected double amplitude in 100 cycles	4.29 RQO
Highest expected double amplitude in 200 cycles	4.60 RQO
Highest expected double amplitude in 1000 cycles	5.26 RQO

Definitions

σ^2 = Statistical variance of time history

N = Number of successive amplitudes

CONSTANT = $\sqrt{2}\,(\ln N)^{1/2}$, where CONSTANT relates σ to the highest expected amplitude in N successive amplitudes

NOTE: The highest expected amplitude in N amplitudes is the most probable extreme value in N amplitudes. This value may be exceeded 63 percent of the time.

SEA STATE DEFINITION

Sea State	Sig. Wave Ht., ft
1	0.0 - 1.9
2	1.9 - 4.1
3	4.1 - 5.7
4	5.7 - 7.4
5	7.4 - 13.0
6	13.0 - 20.8
7	20.8 - 40.3
8	40.3 - 61.6

TABLE 2 - SHIP PARTICULARS

LPH-9 GUAM 1/2 DEGREE TRIM, (BOW UP)

SHIP LENGTH(LBP)	L	556.00	FEET	LENGTH/BEAM	6.619
MAXIMUM BEAM*	B	84.00	FEET	BEAM/DRAFT	3.241
MAXIMUM DRAFT*	T	25.92	FEET	DRAFT/BEAM	.309
DISPLACEMENT	W	17681	TONS,SW	W/(.01L)**3	102.871
DESIGN SPEED	V	20	KNOTS	FROUDE NUMBER	.252
VERTICAL CG	KG	30.96	FEET	KG/BEAM	.369
METACENTRIC HT.	GM	4.99	FEET	GM/BEAM	.059
LONGITUD. CG**	LCG	12.03	FEET	LCG/LENGTH	.043
ROLL GYRADIUS	RRG	32.29	FEET	RRG/BEAM	.384
PITCH GYRADIUS	PRG	139.00	FEET	PRG/LENGTH	.250
YAW GYRADIUS	YRG	139.00	FEET	YRG/LENGTH	.250
EST. ROLL PERIOD		16.02	SECS	ROLL FREQ.(RAD)	.392
TRANSOM WIDTH	TW	24.80	FEET	TW/BEAM	.295
WATERPLANE AREA	AWP	62279	SQ. FEET	AWP/(LB)	1.333
WETTED SURFACE	WS	47735	SQ. FEET	WS/(2LT+2BT+LB)	.598
LONGITUD. CB**	LCB	12.03	FEET	LCB/LENGTH	.043
LONGITUD. CF**	LCF	-.02	FEET	LCF/LENGTH	-.000
VERTICAL CB	KB	14.51	FEET	KB/BEAM	.173
METACENTER	KM	35.95	FEET	KM/BEAM	.428
BLOCK COEFF.	CB	.51			
SECTION COEFF.	CX	.92			
PRISMATIC COEFF.	CP	.56			

* AT STA. 11.00

** AFT OF MIDSHIPS

TABLE 3 - USS GUAM AIRCRAFT OPERATION DELAYS AND CANCELLATIONS

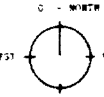
1.	Rain	Delay
2.	Rain	Delay
3.	Rain	Cancel
4.	Rain/Possible Ice Conditions	Delay
5.	Fouled Deck Helo Disabled-Tire	Delay
6.	Motion Roll = 20° DA	Delay - Cancel
7.	Excess, WOD	Cancel
8.	Rain, Fog = Bad Visibility	Cancel
9.	Motions + Weather, Water Over Bow	Delay - Cancel
10.	Motions	Delay
11.	Rain A/C Pace Slowed Down	Delay
12.	Icing	Delay
13.	Red Flare	Delay
14.	Unknown Cause → No	Delay
15.	AV8 Deck Handling	Delay
16.	Seas - Motions - Hard to Predict Bow Position	Delay
17.	Radar Down	Cancel
18.	Wind, Nonuse of Elevators, Motions	Cancel
19.	Pilot	Cancel
20.	A/C Ext Tank Difficulty/Uncertainty	Cancel
21.	Motions	Delay
22.	Motions	Cancel
23.	Snow	Cancel
24.	Fog	Cancel
25.	Radar Out	Cancel
26.	Fog	Cancel
27.	Fog + Freezing Rain	Cancel
28.	Fog + Snow	Cancel
29.	Lack of A/C up, i.e. Helo's	Cancel
30.	Rain, Fog	Cancel

WEATHER	- Rain, Fog, Ice, Visibility, WOD	(15)
OTHER, MISCELLANEOUS	- Ship/AC Equipment and Miscellaneous	(9)
SHIP MOTIONS	- Roll, Pitch, Relative Bow Motion Prediction Difficulty with Bow	(6)

TABLE 4 - HARRIER OPERATION CANCELLATIONS OR DELAYS DUE TO SHIP MOTIONS

TRIAL PARTICULARS				SHIP, WIND, AND SEA CONDITIONS										SHIP MOTIONS[5]				COMMENTS
Cancellation or Delay I. D. Number	Aircraft Event Type Harrier = V Non Harrier = H	Date 1972	Time	Ship Speed Knots[1]	Ship Course Deg	Relative Heading To Swell	Type Sea	Surface Wind Dir Speed Deg/Knots[2]	Relative Wind WOD Knots[3]	Swell Dir/Per/Ht Deg/Sec/Ft[4]	Sea Per/Ht Sec/Ft[4]	Wave Height Sea Plus Swell Ft	Sea State	Pitch $\sqrt{\sigma_0}$ Deg.	Roll $\sqrt{\sigma_0}$ Deg	Vert. Acc $\sqrt{\sigma_a}$ g	Lat. Acc $\sqrt{\sigma_c}$ g	
1	V	14 Jan	1430	16	175	125°	55° Bow	310/09	11-14	050/08/07	03/01	7	4	1.21	0.44	0.032	0.010	Delay to wait for lull in pitch motion.
2	V	14 Jan	1645	14	218	212°	32° Bow	290/05	12	050/08/08	03/01	5	5	1.27	0.82	0.085	0.019	Harrier operations canceled due to large pitch motion--Harrier fly-on from beach is landed. At 1900 all aircraft operations canceled due to large rolls.
3	V	17 Feb	1300	8	305	175°	Head	320/32	38-39	310/07/08	03/04	9	5	1.71	0.90	0.071	0.025	Harriers shifted from condition 4 to 5. Large pitch motions. Elevators cannot be used due to waves hitting openings - spray over bow
4	V	17 Feb	1400	8	305	185°	Head	320/31	38	310/07/08	03/04	9	5	1.81	1.45	0.077	0.027	Delays due to large pitch, continued spray over bow. Handling of aircraft is very difficult and being kept to a minimum.
5	H	17 Feb	1800	12	310	160°	Head	310/25	35-40	310/07/12	03/06	12	5	1.64	0.85	0.071	0.022	All operations canceled due to large pitch motions and spray over bow. Returning aircraft parked on deck--no elevator moves.
6	H	12 Apr	0800	12	160	140°	40° Bow	190/27	-	120/06/03	02/03	4	3	0.50	0.61	0.037	0.028	Scheduled Harrier launch canceled due to wind and motion combined with handling problem--no elevator moves.
7	V	16 Apr	1240	5	185	115°	65° Bow	190/35	36-44	120/06/04	02/06	6	4	0.36	0.63	0.025	0.013	Delays required to "time" bow in attempt to provide bow up takeoffs.
8	V	16 Apr	1400	5	275	105°	75° Beam	260/31	31-38	200/06/04	02/04	6	4	0.50	0.70	0.043	0.024	Two Harriers takeoff. Following two takeoffs canceled. Reason given first two went off bow down.
9	V	10 Apr	1830	7	265	115°	45° Bow	260/32	35-38	200/06/05	02/04	6	4	0.31	0.52	0.034	0.019	All aircraft canceled due to ship radar problem and increasing loss of position
10	H	10 Apr	2230	6	270	160°	20° Bow	260/35	43-45	250/07/07	04/06	9	5	1.20	0.91	0.055	0.024	Radar is back on line, cancellation continues due to loss of position and ship motions
11	V	11 Ap	2100	12	80	150°	30° Bow	270/19	27-34	250/07/07	04/03	7	5	1.55	0.67	0.064	0.016	One harrier takes off, second Harrier canceled. Reason given deck motion too unpredictable. Harrier does two touch-and-go before final
12	V	15 Apr	1340	10	255	125°	55° Bow	230/21	39-43	200/07/05	03/03	6	4	1.54	0.64	056	0.023	Delay to wait for lull in pitch motion. Launch okay.
13	V	15 Apr	1430	12	252	128°	52° Bow	235/27	40-42	280/07/05	03/03	6	4	1.38	1.05	0.069	0.024	Delay to wait for lull in pitch motion. Landing okay
14	H	15 Apr	1500	10	255	155°	25° Bow	250/32	42	230/07/09	03/05	10	5	1.95	1.27	0.077	0.023	Harriers shifted from condition 4 to 5 due to deck motions
15	H	15 Apr	1700	10	265	145°	35° Bow	260/33	42	230/07/07	03/07	10	5	2.00	12.75	0.068	0.042	All aircraft operations canceled due to large deck motions. Returning aircraft parked on deck. No elevator moves

[1] Ship speed from NSRDC measurements or calculated from ship's data.
[2] True wind calculated by ship's Meteorology Office on an hourly basis.
[3] Wind over deck is taken directly from the repeaters in PRI-FLY during the events.
[4] Sea and swell taken from hourly observations of ship's Meteorology Office.
[5] Obtained from spectral analysis of ship motions within ±15 minutes of time of delay or cancellation.



APPENDIX A

GUAM ANTI-ROLL TANK TRIAL RESULTS

Due to the heavy schedule of the GUAM as the Interim Sea Control Ship, the length of time required to conduct comprehensive anti-roll tank evaluation maneuvers, and the generally very low (unsatisfactory) seas, only four rather limited maneuvers or test series were accomplished.

Ideally, an anti-roll tank evaluation trial should be conducted in a series of statistically unchanging seas. That is, a particular unchanging or stationary sea would be characterized by a fixed wave energy distribution over frequency and space, i.e., a fixed wave energy spectrum. Under these conditions it would not matter the order in which test variables such as ship speed, heading, and roll tank water level were varied. Unfortunately, however, sea conditions may vary substantially over a three or four hour interval. Ship heading and speed variations are easier and less time consuming than tank water level variations.

The size and location of the tank is given in Figure A1. Tank size was established from measurements made on the tank during the instrumentation installation on the GUAM. The GUAM's tank, which has an 831 ft^2 free surface, requires the pumping of about 6220 gallons of water to change the water level one foot. In this context it should be noted that two to three foot water level changes are required before substantial effects on roll may be expected. Therefore, the pumping of these large quantities of water required so much time that tank water level changes were the least frequently varied test parameter. As a

result of this, and the generally short test time allowed by the GUAM's schedule, test series were generally conducted only at a single water level. The four test series were, in fact, made during three separate at sea periods and on four different days. Thus, it was not possible to run test series at two different water levels successively so as to minimize the time lag between tests at these water levels.

A time lag between successive test series introduces two errors in the evaluation of the tank. The first is the variation in sea conditions with time. This variation in itself may produce variations in roll as large, or larger than, the ones brought on by the change in water level. The second error is associated with the change in roll due to variation in ballast condition with time. Here ballast condition denotes a specific GM, transverse gyradius, and draft.

It is considered unlikely that a significant change in the GUAM's roll response resulted from the variation in ballast condition during a given at sea period. Thus, if variations in sea conditions are properly accounted for, the results for all test series during a specific at sea period are comparable.

Results for test series conducted during different at sea periods are less likely to be directly comparable. The reason is that ballast conditions from one short at sea period to the next (and therefore the roll response) is expected to be more variable than the ballast condition during a given at sea period.

ANALYSIS PROCEDURE

To properly account for variations in sea conditions, direct or indirect measures of wave height are required. Since a component of the wave height sensor (relative bow motion) did not function properly during these trials, indirect measures of wave height had to be used. Pitch and bow acceleration were therefore selected to replace wave height as the parameter by which wave height variability might be accounted for in the roll results.

Pitch and bow acceleration were selected because they show the effect of wave height variations but are not affected by increases or decreases in the ship's roll. Thus, the action of the roll tank will not affect their variation with wave height. Only speed and heading, or equivalently, shifts in the peak of the encountered wave spectrum, will affect the wave height variations reflected in pitch, bow acceleration and roll. It is important to note, therefore, that roll tank effectivenesss as measured by the ratio of roll to pitch and roll to bow acceleration is valid only for a particular speed and heading. Roll magnitude comparisons are valid only as a function of tank depth for a fixed heading and speed.

Characteristic amplitude or double amplitude statistics which describe the irregular wave or ship response magnitudes are related to RMS or $\sqrt{Q_0}$ values of wave or response time histories by the constants of Table 1. The double amplitude constants may thus be used with the $\sqrt{Q_0}$ values of ship responses to obtain average ship responses, significant

ship responses, i.e., the average of the one third highest responses, or the highest responses in 10, 20, 50 or more cycles of ship responses. In this connection it should be noted that a single amplitude is defined as the extreme value between two successive mean crossings of the time history. Similarly, a cycle is defined by three successive mean crossings, and the double amplitude is the sum of the absolute value of two successive single amplitudes.

TRIAL RESULTS

The results of the four test series are given in Table A1 and A2. Table A1 presents the ship motion results in terms of the $\sqrt{Q_0}$ values as well as the static values of pitch (trim) and roll (heel). Table A2 on the other hand presents the ship motions in terms of the maximum double amplitudes observed during the test runs, as well as the maximum bow down pitch excursion noted during the run. Run times are also given.

It should be noted that Figure A2 presents roll per unit pitch and per unit bow acceleration as a function of tank water depth at 5 knots and 12 to 13 knots. The ship with a full tank of water, i.e., 14.75 feet, represented the unstabilized condition. Table A3 on the other hand was prepared to demonstrate the tank effectiveness at various headings and ship speeds. Results are again tabulated in terms of roll per unit pitch and per unit bow acceleration.

DISCUSSION OF TRIAL RESULTS

It is quite clear from the tabulated ship motions (Tables A1,

A2) that the seas during the anti-roll tank maneuvers were quite mild. In most of the cases the maximum bow down excursion did not even depress the bow below the even keel position due to the static bow up trim of about 1.2 degrees. Tests were conducted at a low speed of 5 knots and intermediate speeds of 12 and 13 knots. The 5 knot test generally resulted in maximum double amplitude roll angles of less than 3 degrees. Therefore when these 5 knot results are examined, it is not surprising to find little or no roll stabilization (see Figure A2 and Table A3, 5 knots beam seas).

When the ship speed was increased to 12 or 13 knots, however, roll stabilization due to the tank appeared to increase significantly (see Table A3 and Figure A2). This stabilization is reflected both in the roll whic has wave variability minimized (roll/pitch, roll/bow acceleration), and in the maximum roll. In fact, roll reductions on the order of 80 percent were obtained in beam seas based on the unstabilized roll/pitch and roll/bow acceleration. A similar, though somewhat lower, degree of stabilization was also obtained in bow and quartering seas. Specifically, roll stabilization of more than 60 percent was obtained in bow seas and more than 65 percent was obtained in quartering seas. The 12 knot quartering sea test results shown in Figure A2 tend to substantiate the roll stabilization obtained by the GUAM's anti-roll tank. It is concluded therefore that at least for the encountered sea conditions the GUAM's anti-roll tank did serve to reduce roll significantly at 12 and 13 knots.

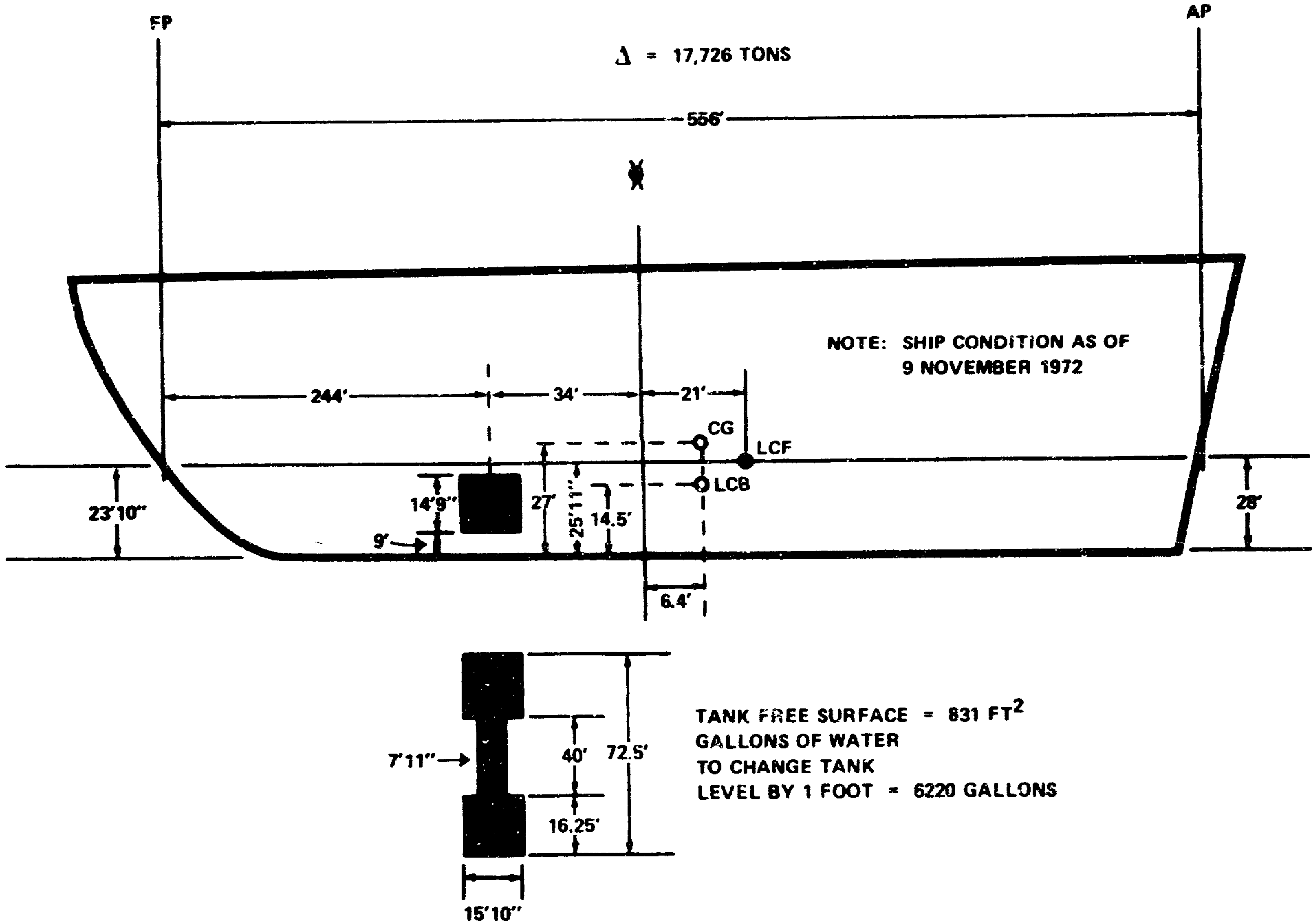


Figure A1 - GUAM Anti–Roll Tank Size and Location

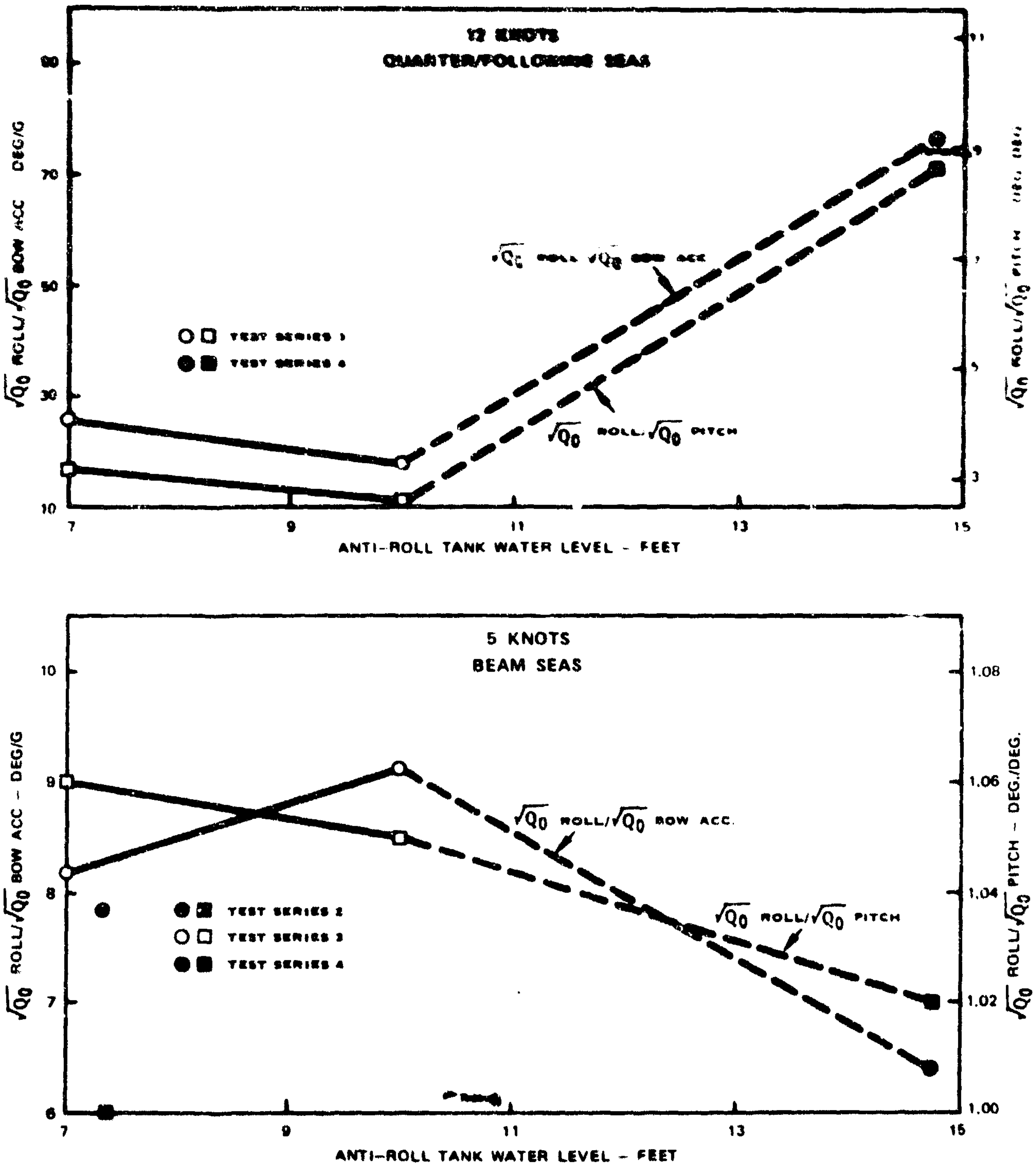


Figure A2 - Effect of Tank Depth on Roll Motion of GUAM

TABLE A1- USS GUAM ANTI-ROLL TANK TRIALS DATA $\sqrt{Q_o}$ RESULTS

Test Series No.	Run No.	Date and Run Time	Speed and Heading Knots	Water Depth in Tank	Pitch $\sqrt{Q_o}$ Deg.	Pitch Trim (- Bow Up) Deg.	Roll $\sqrt{Q_o}$ Deg.	Roll Heel (- Port Up) Deg.	Bow Vertical g's	$\sqrt{Q_o}$ Accelerations Vertical* g's	Longitudinal* g's	Lateral* g's
1	42	9 Feb 72 1017	0 Head	Full 14'8"	0.52	-1.19	0.51	.01	.080	.030	.009	.015
	43	1049	5 Bow	"	0.65	-1.23	0.59	1.31	.105	.047	.012	.028
	44	1117	13 Bow	"	0.36	-1.23	0.83	1.80	.034	.052	.013	.028
	45	1147	13 Beam	"	0.34	-1.25	1.63	1.82	.044	.028	.007	.020
	46	1217	13 Quart/F	"	0.14	-1.24	1.33	0.59	.019	.011	.003	.010
	47	1257	5 [illegible]	1/2 Full 7'4"	0.37	-1.24	0.81	-1.86	.064	.028	.008	.014
2	58	10 Feb 72 1913	5 Bow	1/2 Full 7'4"	0.43	-1.08	0.28	-0.53	.050	.020	.005	.007
	59	1943	13 Bow	"	0.55	-1.06	0.35	-1.07	.097	.029	.011	.008
	60	2015	13 Beam	"	0.78	-1.08	0.68	-1.55	.123	.050	.013	.025
	61	2058	5 Beam	"	0.69	-1.08	0.69	-1.53	.088	.042	.009	.025
	62	2130	5 Quart/F	"	0.49	-1.08	0.93	-1.39	.058	.035	.006	.025
	63	2233	13 Quart/F	"	0.47	-1.09	1.54	-1.63	.160	.036	.007	.004
3	75	8 Mar 72 1519	5 Beam	2/3 Full 10'	1.07	-1.27	1.13	1.07	.124	.070	.010	.045
	79	1548	12 Quart/F	2/3 Full 10'	0.61	-1.27	1.59	0.64	.089	.041	.010	.030
	80	1707	5 Beam	1/2 Full 7'	1.01	-1.31	1.08	0.53	.132	.067	.012	.046
	81	1730	12 Quart/F	1/2 Full 7'	0.71	-1.30	2.24	0.10	.037	.048	.009	.036
4	83	20 Apr 72 1832	5 Head	Full 14'8"	0.21	-1.33	0.36	0.55	.034	.017	.005	.009
	84	2006	5 Beam	"	0.52	-1.33	0.53	-1.36	.083	.052	.009	.031
	85	2042	12 Quart/F	"	0.25	-1.33	2.15	-0.90	.028	.015	.005	.016

*Acceleration measurements for a point one deck below normal aft starting/landing position on centerline 36 feet forward of aft perpendicular.

TABLE A2 - USS GUAM ANTI-ROLL TANK TRIALS DATA MAXIMUM DOUBLE AMPLITUDES

Test Series No.	Run No.	Date and Run Time	Speed and Heading Knots	Water Depth in Tank	Pitch Deg.	Roll Deg.	Bow Vertical g's	Maximum D.A. Accelerations Vertical* g's	Longitudinal* g's	Lateral* g's	Test Duration Minutes	Maximum Pitch Bow Down Excursion Deg. (- Bow Up)
		9 Feb 72										
1	42	1017	0 Head	Full 14'8"	2.12	1.34	.27	.12	.032	.061	12.77	- .14
	43	1049	5 Bow	"	2.49	2.47	.27	.20	.044	.132	19.87	- .07
	44	1117	13 Bow	"	1.61	3.65	.44	.26	.062	.132	24.83	- .33
	45	1147	13 Beam	"	1.70	6.27	.19	.13	.032	.110	23.88	- .30
	46	1217	13 Quart/F	"	0.67	5.28	.03	.05	.014	.043	29.80	- .90
	47	1257	5 ?	1/2 Full 7'4"	1.39	1.08	.24	.12	.030	.051	5.18	- .57
		10 Feb 72										
2	58	1913	5 Bow	1/2 Full 7'4"	2.09	1.34	.20	.08	.022	.033	19.88	- .05
	59	1943	13 Bow	"	2.70	2.47	.45	.13	.051	.036	19.88	+ .18
	60	2015	13 Beam	"	3.10	3.65	.55	.22	.061	.109	24.85	+ .35
	61	2056	5 Beam	"	3.20	6.27	.40	.16	.041	.104	24.83	+ .40
	62	2130	5 Quart/F	"	2.01	5.28	.23	.17	.026	.107	25.83	- .11
	63	2233	13 Quart/F	"	2.12	1.08	.27	.16	.034	.127	27.83	+1.93
		6 Mar 72										
3	78	1519	5 Beam	2/3 Full 10'	4.12	5.47	.56	.40	.045	.202	16.05	+1.42
	79	1548	12 Quart/F	2/3 Full 10'	2.50	6.45	.45	.17	.051	.126	21.87	- .22
	80	1707	5 Beam	1/2 Full 7'	4.90	3.92	.60	.33	.061	.194	19.88	+ .96
	81	1730	12 Quart/F	1/2 Full 7'	2.93	10.39	.37	.20	.043	.154	19.88	+3.82
		20 Apr 72										
4	83	1632	5 Head	Full 14'8"	.96	1.14	.16	.07	.020	.043	19.95	- .78
	84	2000	5 Beam	"	2.30	1.95	.43	.25	.049	.141	29.82	- .31
	85	2042	12 Quart/F	"	1.00	8.30	.12	.07	.027	.063	29.88	- .77

*Acceleration measurements for a point one deck below normal aft starting/landing position on centerline 36 feet forward of aft perpendicular.

TABLE A3 - TANK EFFECTIVENESS AT VARIOUS HEADINGS AND SHIP SPEEDS

Heading	12 - 13 Knots				5 Knots			
	Roll/Pitch		Roll/Bow Acc.		Roll/Pitch		Roll/Bow Acc.	
	Full	1/2 Full	Full	1/2 Full	Full	1/2 Full	Full	1/2 Full
Bow	2.30	0.60	8.82	3.60	0.98	0.58	5.62	5.60
Beam	4.79	0.87	37.0	5.53	1.02	1.00	6.39	7.84
Quartering	9.50	3.27	70.0	9.62	--	1.89	--	16.03

NOTE: Measures of roll performance cannot be compared as a function of speed or heading. Comparison of magnitudes are valid only as function of tank depth.

APPENDIX B

GUAM SHIP MOTION/VERTICAL VELOCITY PREDICTIONS AT VARIOUS POINTS ON SHIP

INTRODUCTION

The following ship motion predictions were made for the GUAM's December 1972 deployment. The predictions were made in order to assess systematically the sensitivity of the ship responses to operator controls, i.e., alterations in heading and ship speed.

The calculations of motions were made for five ship speeds, i.e., 0, 5, 10, 15, and 20 knots in long crested seas at 6 headings varying from head seas (180°) to quartering seas (30°) in 30 degree increments. Although all motions were computed, only the vertical velocities at a series of 10 specific points on the ship, as well as pitch and roll were examined in detail and are reported.

SHIP PARTICULARS

The characteristics and load conditions of the GUAM are presented in the text of the report (see Table 2). It should be noted that the load condition is representative for the ship at its normal at sea deployment (without a large complement of troops).

Details of the locations for which motion and velocity predictions are made are shown in Figure B1. It may be noted that these predictions are made for various (10) positions which have particular importance in the aircraft operational cycle on board the ship.

Point 4, 5, 9, and 10 refer to where aircraft are being moved either up from the hangar deck to the flight deck, or down, by use of the forward and aft deck edge elevators.

Point 1 refers to the aftmost usable location on the flight deck and Point 2 to the foremost usable location on the flight deck. The nozzle rotation line for the Harrier passes through Point 2. Bow landings have been made at various times by the Harriers at Point 8.

Point 3 refers to the midship location on the flight deck. Points 6 and 7 refer to the range of normal starting locations for the rolling takeoffs of the Harriers. In general, the majority of the Harrier operations (landing and takeoffs) are conducted in the area between Point 3 and 6. As the ship motions increase, operations tend to move towards Point 3.

CALCULATION PROCEDURE

Ship Response

The motion responses of the GUAM were computed in regular waves using the NSRDC Ship Motion and Sea Load Computer Program. The resultant ship response transfer functions were then used as input to NSRDC Irregular Sea Response Prediction Computer Program to calculate the RMS ship responses in irregular, long crested seas.

Sea Representation

The seas were analytically represented by long crested, two-parameter wave spectra of the form developed by Bretschneider (see

reference 4). Modal wave periods ranging from 9 to 12.1 seconds with a 35.4 feet significant wave height were used. Here the modal wave period represents the period corresponding to the peak of the wave spectra. The range of periods was selected to represent typical storm seas at various stages of development, although none of the seas represent fully developed seas. It was considered unlikely that aircraft operations in seas higher than these 35 foot significant height (high Sea State 7) could be accomplished because the wind speeds (> 45 knots) associated with these partially developed seas would preclude aircraft operations even if ship motions would not.

RESULTS AND CONCLUSIONS

RMS vertical velocities, as well as pitch and roll amplitudes, are presented in Table B1. All responses are amplitudes and thus represent one half of the total range of the ship response. For example, for pitch this means the bow up or the bow down motion and not the bow up plus bow down motion is calculated. Results are shown for speeds of 0, 5, 10, 15 and 20 knots for two rather different ship operator strategies.

The "BEST HEADING" strategy assumes that the ship's captain operates his ship so as to minimize vertical ship accelerations at the various locations within the ship, whereas the "WORST HEADING" strategy assumes that the captain is forced (by the wind or operational constraints) to operate his ship so as to maximize the vertical ship accelerations.

It is considered in both of the operator strategies that the wind is ignored -- a clearly unrealistic assumption. These two strategies

were selected because they represent the extreme range of possibilities open to the ship operator when attempting aircraft operations in the 35 foot seas. It should be noted that the predicted design responses shown in Table B1 are selected according to the best, or worst, modal period for each of the two strategies.

One important feature of the method of data presentation of Table B1 should be kept in mind. The results are directly proportional to the assumed 35.4 ft. significant wave height. Thus for example, if results are desired in 11.8 ft. seas with a similar range of modal wave periods (9.0 to 12.1 seconds) these results can be obtained by simply multiplying the values of the Table by 11.8/35.4.

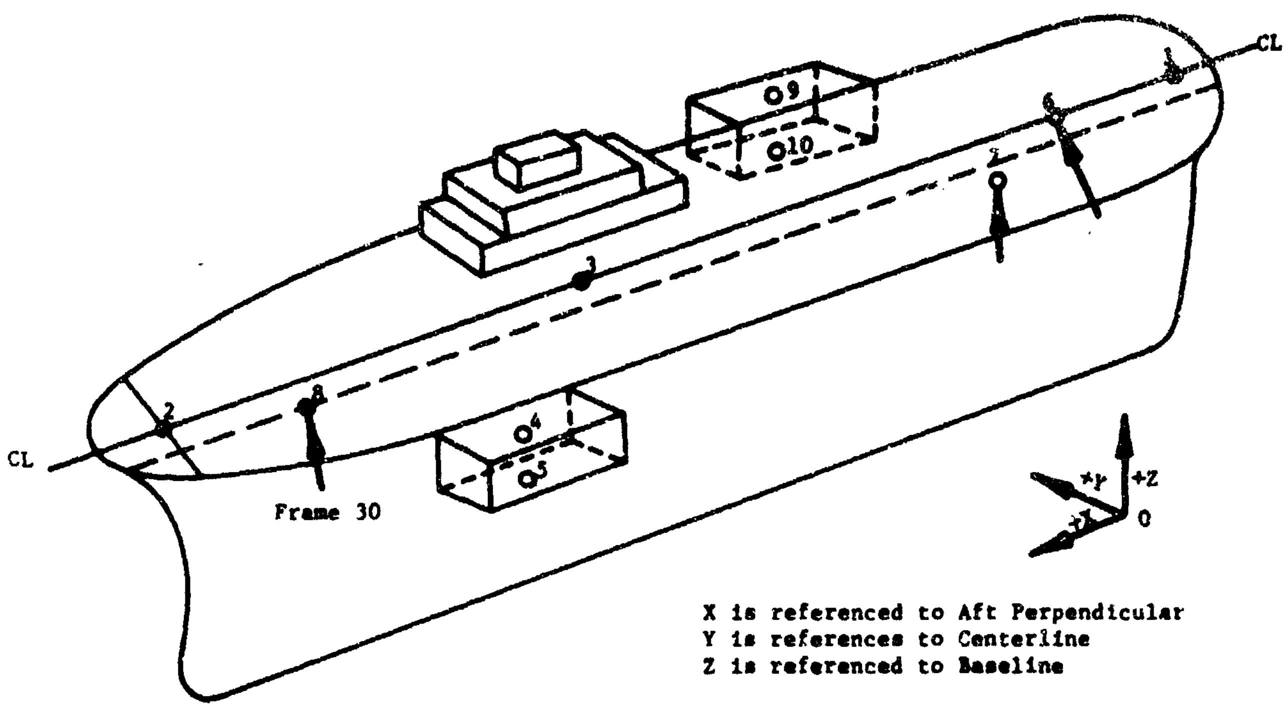
The results indicate clearly that changes in heading have a far greater influence on the vertical accelerations than do the changes in speed. Vertical velocities ranging from about 1 foot/second to 5 feet/second occur at the "best heading" in the most common aircraft landing/takeoff area (Positions 3, 6, 7). The "worst heading" conditions on the other hand result in vertical velocities ranging from 7 feet/second to 11 feet/second in the comparable deck area.

Three cautions with regard to the above values are in order. First, these are not the more extreme motion/response cycles but rather the most frequently occurring motion cycles which the pilots/operators have been able to select in their operations. Thus, if in the higher seas the operators are less successful in timing their operations, they might actually double these values if they happen to land or takeoff during the significant (average of one-third highest) rather than the

most frequently occurring motions. Due to an inadequate mathematical model for roll damping the roll motion values* are rather unrealistically high at speeds above 5 knots. Finally, these predicted values are somewhat high at headings of 120, 90, and 60 degrees because long creted (unidirectional) areas are assumed.

---

* Used to determine the vertical acceleration for these point locations off the centerline of the ship, e.g., points 4, 5, 7, 8, 9, and 10.



Point	Location	X (Feet)	Y (Feet)	Z (Feet)
1	Aft Edge of Flight Deck	-6	0.0	76.5
2	Forward Edge of Flight Deck	+560	0.0	76.5
3	Midship on Centerline	+278	0.0	76.5
4	Center of Forward Elevator in Up Position	+336	-64.5	76.5
5	Center of Forward Elevator in Down Position	+336	-64.5	48.0
6	1st Aft Position for Normal Start Rolling Takeoff	+36	0.0	76.5
7	2nd Aft Position for Normal Start Rolling Takeoff	+108	-14.0	76.5
8	Bow Landing Spot	+436	-14.0	76.5
9	Center of Aft Elevator in Up Position	+160	64.5	76.5
10	Center of Aft Elevator in Down Position	+160	64.5	48.0

Figure B1 - Locations of Points on USS GUAM for which Motion and Velocity Response Predictions were Made

TABLE B1 - PREDICTED RMS VERTICAL VELOCITIES, ROLL AND PITCH ANGLES OF THE USS GUAM

Point	Vertical Velocity, Feet/Second									
	Best Heading					Worst Heading				
	Ship Speed, Knots					Ship Speed, Knots				
	0	5	10	15	20	0	5	10	15	20
1	5.6(180°)	5.0(30°)	3.4(30°)	2.6(30°)	3.7(30°)	11.1(60°)	10.3(120°)	10.6(120°)	11.1(120°)	11.4(120°)
2	7.0(180°)	5.3(30°)	3.8(30°)	3.1(30°)	4.4(30°)	17.9(120°)	15.2(120°)	16.2(120°)	16.9(120°)	17.9(120°)
3	1.4(180°)	1.1(30°)	0.8(30°)	0.8(30°)	1.2(30°)	6.9(90°)	6.9(90°)	6.8(90°)	7.0(120°)	8.0(120°)
4	2.3(180°)	3.0(30°)	3.9(180°)	4.3(180°)	2.3(30°)	7.5(90°)	7.4(90°)	11.3(30°)	15.2(30°)	17.8(60°)
5	2.3(180°)	3.0(30°)	3.9(180°)	4.3(180°)	2.3(30°)	7.5(90°)	7.4(90°)	11.3(30°)	15.2(30°)	17.8(60°)
6	4.7(180°)	4.2(30°)	2.9(30°)	2.3(30°)	3.2(30°)	6.5(90°)	8.7(120°)	9.0(120°)	9.6(120°)	10.8(120°)
7	3.2(180°)	2.7(30°)	1.7(30°)	2.7(60°)	2.8(30°)	6.7(60°)	6.7(120°)	6.9(120°)	7.6(120°)	8.0(120°)
8	4.4(180°)	3.5(30°)	3.2(30°)	3.6(30°)	2.4(30°)	8.6(120°)	9.8(120°)	10.8(120°)	11.8(120°)	12.0(120°)
9	1.8(150°)	2.5(180°)	2.7(180°)	3.1(180°)	1.7(30°)	6.2(60°)	6.3(90°)	9.8(30°)	14.3(30°)	12.7(60°)
10	1.8(150°)	2.5(180°)	2.7(180°)	3.1(180°)	1.7(30°)	6.2(60°)	6.3(90°)	9.8(30°)	14.3(30°)	12.7(60°)
Roll, Degrees	1.6(150°)	1.1(150°)	0.8(150°)	0.6(150°)	0.5(150°)	4.6(120°)	11.7(60°)	21.6(30°)	36.8(30°)	34.0(60°)
Pitch, Degrees	0.3(90°)	0.3(90°)	0.2(90°)	0.2(90°)	0.2(90°)	3.0(120°)	3.1(150°)	3.2(150°)	3.3(180°)	4.8(30°)

Note: Head Seas is defined as 180°, beam seas as 90°, and following seas as 0°.

APPENDIX C

BI-DIRECTIONAL LAUNCH/RECOVERY CAPABILITY OF S.C. SHIPS

Two operational procedures are evident in the wind over deck (WOD) data of Figures 17, 18, 19 and 24. Referring to the right-hand scale, it may be noted that all short takeoffs occurred with a relative wind direction within $\pm 20^{\circ}$ of an absolute head wind which is denoted by 0° on the figure. Secondly, it may be noted by referring now to the left-hand scale of the figure that all short takeoffs also occurred with a relative wind speed of less than 45 knots. These data illustrate that the current* operational restrictions (see reference 3) for the Harriers limit the maximum relative wind speeds to 45 knots for takeoffs and 40 knots for landings. In addition, the aircraft must face essentially directly into the relative wind in all but very light (5 knots and less) relative winds.

These WOD speed and direction restrictions require the operator to change ship course in such a manner that the relative wind is down (bow to stern) the deck at speeds less than 40 (VL) and 45 (STO) knots. This course change is dependent solely on the speed and direction of the existing surface wind. The required course changes may be from 0 to 180 degrees and may require up to six minutes. Since ship speed and surface wind speed are additive vectorially, when a head wind condition is established, the WOD speed restriction may require that the operator reduce ship speed to maintain a relative wind speed of less than 40-45 knots.

Currently, when surface winds of 45 knots or more are encountered, Harrier operations must be cancelled regardless of ship motions. A

---

* April 1973

significant improvement in operational capability for the SCS would be gained if the impact of these two operational restrictions could be reduced. Such a reduction in impact can be obtained by adding a bi-directional capability to the SCS design. That is to allow for bow to stern operations as well as the current stern to bow capability. The most significant increase in operational capability would be the added ability to launch and retrieve Harriers when surface winds are above 40-45 knots. This would be accomplished by using the available ship speed to decrease the relative wind velocity as shown in Figure C 1. As is shown in the figure, Harrier launches from stern to bow cannot be conducted when surface winds are 40 knots or above. However, with a bi-directional capability, operations can be continued by using available ship speed to reduce the relative wind over deck.

The importance of this additional capability may be realized more fully by a simple example. If wind speed is considered to be the only source of restrictions in aircraft operations, estimates of the maximum total number of operational days can then be made based on an existing wind atlas or data base. These estimates of course will be too high, but will serve as a basis for comparison of a SCS operating with and without a bi-directional landing and takeoff capability.

A SCS operating in the North Atlantic area, defined by a southern boundary from New York to Spain, northern boundary in the area of Iceland, and east-west boundaries defined by land masses, would encounter surface winds in excess of 34 knots (Beaufort 8) approximately 9 percent of the time (see reference 4) throughout a calendar year.

Assuming a ship speed of 6 knots is required for steerage, we have a relative wind of 40 knots or more down the deck when launching from stern to bow, i.e., wind from the bow. This means that approximately 9 percent of the time Harrier operations would not be permitted under current restrictions. Thus, we have an average of 335 operational days in a year. With a bi-directional capability Harrier operations could continue with surface winds up to 60 knots assuming a ship speed capability of 20 knots. Sixty knot or greater winds occur less than 0.3 percent of the time in the area under considration. This increase in allowable surface wind increases the average number of operational days to 364 a year.

In the previous example, the addition of a bi-directional capability will add an average of 29 days a year to the operational calendar of the SCS based on wind restrictions now applicable to Harrier operations. Bi-directionality also allows the operator to choose from two possible ship courses during Harrier operations, i.e., bow to stern or 180 degrees away for stern to bow. This choice would be influenced by three major factors: first is the allowable wind speed as just discussed; second, the relative sea direction while on course and its effect on ship motions; and third, the relative direction of intended movement for the ship. Unidirectional restrictions do not allow such a choice to be made. Thus, under unidirectional restrictions the operators may be forced to cancel operations due to excessive winds, accept a heading relative to the sea which produces ship motions unfavorable to aircraft operations, and/or accept a course which does not allow the SCS to maintain a desirable position relative to a convoy.

All of these situations have been encountered during the NSRDC observation period on board the GUAM.

So far the discussion has been limited to the occurrence of surface winds and their effect on Harrier operations. It is reasonable to assume that as surface winds increase the sea will grow more hostile. In fact, a fully developed sea in the open ocean generated by a 34-40 knot wind will consist of waves approaching 50 feet (peak to trough). Certainly, in a seaway of this magnitude ship motions would be a consideration in aircraft operations. It must be noted, however, that the occurrence of a 40 knot surface wind does not immediately produce a large seaway. To produce a fully arisen seaway such a wind must exist for approximately 37 hours. Thus, the ability to launch and retrieve aircraft in such a wind is advantageous until such time that the seaway itself is of sufficient magnitude to cause cancellations.

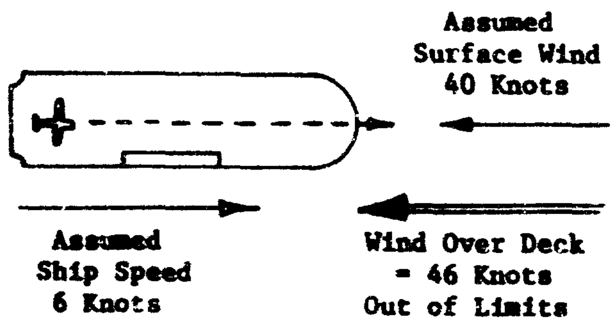
Yet another consideration is the ability of the operator to predict ship motions on the two possible ship courses available under bidirectional operations. For example, if the choice is between a head sea or a following sea the accuracy with which a lull, or a bow up condition can be predicted for the two headings will then determine the course. Experience aboard the GUAM has shown that the operator's ability to predict accurately is generally a function of seaway and of relative heading.

As has been established in the main text, flight operations are more sensitive to pitch than to roll, while handling and maintenance are more sensitive to roll than pitch. This fact should also be consid-

when deciding between two permissible courses.

In summary, while a bi-directional capability does not solve operational problems associated with high winds and seas, it does increase operational time and does allow some flexibility in solving ship motion and ship position problems.

Uni-directional Capability: Stern to Bow Only



Comments:

1. AV-8 operations cease with 40 knot surface winds.

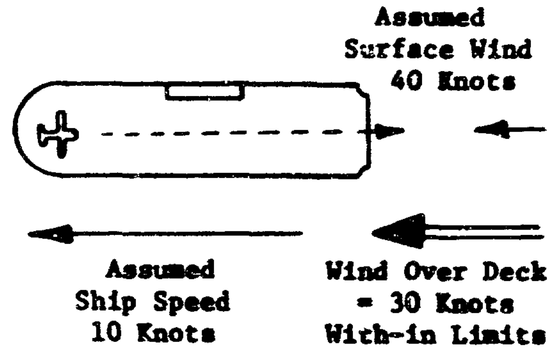
2. Course corrections of 180 degrees may be required to obtain 0 degree relative wind over deck.

3. Ship speed must be reduced as surface wind increases to maintain operational limits.

4. Ship may lose position in convoy due to required course and speed changes.

5. Operator has no choice of relative heading.

Bi-directional Capability: Stern to Bow and Bow to Stern



Comments:

1. AV-8 operations cease with 60 knot surface winds (assumed 20 knot ship speed).

2. Course corrections will never exceed 90 degrees if bi-directional operations can be performed.

3. Operator has choice of relative heading and speed if bi-directional operations are available allowing ship to better maintain position and/or reduce ship motions during operations.

Figure C1 - Comparison Between Uni-directional and Bi-directional Operational Capabilities.

REFERENCES

1. Randolph, Hazel E., "Development of Math Model - SEACORR," ORI Report Prepared under Contract No. N00167-72-M-4827 (July 1973).

2. Baitis, A. E., "Influence of Ship Motions on Operations of SH-2F Helicopters from DE-1051 Class Ships: Sea Trial with USS Bowen (DE 1079)" NSRDC Ship Performance Department Report 556-01 (July 1975).

3. NAEC AV-8A Shipboard Operating Bulletin #2 (December 1972).

4. "Estuary and Coastline Hydrodynamics, "Edited by Arthur T. Ippen, McGraw-Hill, Inc., (1966), "Wave Generation by Wind, Deep and Shallow Water," (C.L. Bretscheneider), pp. 133-196.

5. Report of 5th International Ship Structures Congress - Committee 1, "Environmental Conditions" (1972).

DTNSRDC ISSUES THREE TYPES OF REPORTS

(1) DTNSRDC REPORTS, A FORMAL SERIES PUBLISHING INFORMATION OF PERMANENT TECHNICAL VALUE, DESIGNATED BY A SERIAL REPORT NUMBER.

(2) DEPARTMENTAL REPORTS, A SEMIFORMAL SERIES, RECORDING INFORMATION OF A PRELIMINARY OR TEMPORARY NATURE, OR OF LIMITED INTEREST OR SIGNIFICANCE, CARRYING A DEPARTMENTAL ALPHANUMERIC IDENTIFICATION.

(3) TECHNICAL MEMORANDA, AN INFORMAL SERIES, USUALLY INTERNAL WORKING PAPERS OR DIRECT REPORTS TO SPONSORS, NUMBERED AS TM SERIES REPORTS; NOT FOR GENERAL DISTRIBUTION.